AFRL-RB-WP-TM-2011-3073

MIDWEST STRUCTURAL SCIENCES CENTER
2010 Annual Report

William A. Dick

University of Illinois

JUNE 2011
Interim Report

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
AIR VEHICLES DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Wright-Patterson Public Affairs Office and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RB-WP-TM-2011-3073 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//signature//

S. MICHAEL SPOTTSWOOD
Senior Aerospace Engineer
Analytical Mechanics Branch
Air Force Research Laboratory

*//signature//

MICHAEL J. SHEPARD, Chief
Analytical Mechanics Branch
Structures Division
Air Force Research Laboratory

*//signature//

DAVID M. PRATT, PhD
Technical Advisor
Structures Division
Materials & Manufacturing Directorate

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

*Disseminated copies will show "//signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS**.

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2011	Interim	01 October 2009 – 30 September 2010

4. TITLE AND SUBTITLE
MIDWEST STRUCTURAL SCIENCES CENTER
2010 Annual Report

5a. CONTRACT NUMBER
FA8650-06-2-3620

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62201F

6. AUTHOR(S)
William A. Dick

5d. PROJECT NUMBER
2401

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
A0DK0A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Illinois
Midwest Structural Sciences Center
2276 Digital Computing Lab
Urbana, IL 61801

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Air Vehicles Directorate
Wright-Patterson Air Force Base, OH 45433-7542
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RBSM

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RB-WP-TM-2011-3073

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PAO Case Number: 88ABW 2011-3502, cleared 20 June 2011. Document contains color.

14. ABSTRACT
The Midwest Structural Sciences Center is the collaboration between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM SSC), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University, University of Cincinnati, and the University of Texas at San Antonio. The team works closely to simulate, model, and test structures and materials for use in future air-and space-vehicles in a risk quantified design process.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	40	Dr. S. Michael Spottswood / N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Midwest Structural Sciences Center

University of Illinois at Urbana-Champaign
University of Texas at San Antonio
Wright State University
Structural Sciences Center, U.S. Air Force Research Laboratory

2010 Annual Report

The Midwest Structural Sciences Center is a collaborative effort between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University (WSU), and the University of Texas at San Antonio (UTSA). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and spaceframes focusing on structural response and life prediction.

The University of Illinois Midwest Structural Sciences Center (MSSC) was established in February 2006 to expand rapidly the technical manpower available to the Structural Sciences Center at AFRL. The MSSC has the long-term objective of developing the knowledge base required for validated tools for the design and simulation of coupled aero-thermo-mechanical structures. In close collaboration with the scientific and engineering staff of AFRL/RBSM, faculty, staff and students from the universities undertake medium-term research projects (five- to ten-year horizons) in four key areas:

- Coupled aero-thermo-mechanical-acoustic analysis and simulation of aerostructures
- Identification and definition of structural limit states for spatially-tailored aero-thermo structures
- Computational frameworks and methodologies for risk-quantified structural assessment of spatially-tailored aero-thermo structures
- Experimental discovery and limit state characterization

The team employs analytical, computational, experimental, personnel and financial resources from several university departments and AFRL organizations, and seeks additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and are being applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their AFRL/RBSM colleagues to evaluate and extend the understanding of structures and materials in aerospace structural components that experience extreme combined environments.

MSSC Technical Program Features

Structural response prediction
Structural life prediction
Multiscale materials modeling
Generalized finite element methods
Risk analysis and quantification
Sensitivity analysis
Experimental comparison

MSSC Research Program Partners

Air Force Research Laboratory Air Vehicles Directorate, Structural Sciences Center
University of Illinois at Urbana-Champaign
Aerospace Engineering
Civil and Environmental Engineering
Computational Science and Engineering
Mechanical Science and Engineering
Wright State University
University of Texas at San Antonio

Approved for public release; distribution unlimited.

1 Introduction

1.1 Air Force Structural Sciences Mission

Future missions of the United States Air Force (USAF), such as prompt global strike and operationally responsive space access, will be performed with air/space vehicles now in conceptual design. However it is clear that the structural concepts needed to make such next-generation vehicles sufficiently durable and lightweight will involve novel structural arrangements and material systems. During typical operating conditions, aircraft are subjected to random loads due to engine noise and other aeroacoustic vibrations. The random aeroacoustic pressure load, combined with other extreme conditions like elevated temperatures, turbulence, etc., may lead to the failure of the aircraft structure. Challenges in predicting the response of structures in extreme environments include aerothermoelastic coupling; computational cost and complexity of large models; material nonlinearity, temperature dependence and degradation; spatial variation of material and structural properties; and uncertainty in loads, material properties, geometry, and boundary conditions.

The goal of the USAF Structural Sciences Center (SSC) is to provide an improved understanding of structural response, damage progression and failure in a non-deterministic simulation framework. This framework is thought necessary for the development of revolutionary and durable aero-thermal structures. Future Air Force vehicle designs will require structures that can withstand extreme transient aerothermal and dynamic, aeroacoustic environments. Examples include vehicles exposed to launch, sustained hypersonic velocities, re-entry, and stealth aircraft with buried engines and ducted exhaust. These future vehicles will have to be designed using different tools than the vehicles of today. The fleet sizes for these vehicles will diminish, and the number of vehicles for a particular design will be necessarily small. The USAF will no longer have the luxury of building pre-production vehicles to conduct extensive structural testing. Even if a full-scale vehicle were made available for structural testing, no test facility currently exists capable of exactly replicating the extreme environments experienced during service. Further, the statistical significance of a single static and/or durability test is suspect. The USAF must rely on a combination of component/system tests and numerical tools for design and certification.

The goal of the Air Force SSC research program is to provide high-fidelity simulation tools for the design of high-performance aerospace structures in extreme, combined-environments. The focus, both internal and extramural, is on representative or benchmark structures with levels of combined loading appropriate for exercising specific phenomena, e.g., geometrically nonlinear response, material nonlinearities, and static and dynamic instabilities. A long-term challenge for structural science is the capability to predict the response and life of a structure in a combined thermal-mechanical-vibratory environment. This includes the simulation and prediction of damage progression of a structure throughout a high-performance aerospace vehicle trajectory. A structure in this environment will experience extremely hot surface temperatures, large thermal gradients, transient heating, significant fluctuating pressures, and long-duration exposure to these environments.

Modeling/simulation — Used in reliability analysis, design, and for designing effective experiments

Experiments — Data used for parameter identification studies to improve modeling effort and validation of simulations

Risk/reliability — Algorithms used for reliability analysis, parameter identification and design

1.2 Midwest Structural Sciences Center

The Midwest Structural Sciences Center is a collaborative effort between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University (WSU), and the University of Texas at San Antonio (UTSA). The team

Approved for public release; distribution unlimited.

works closely to simulate, model, test, and assess structures and materials for use in future air- and spaceframes. The MSSC team is viewed as a “living organization” whose members change over time to meet the needs of the collaborative partnership.

The team employs analytical, computational, experimental, personnel and financial resources from all four organizations, and seeks additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and are applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their colleagues at AFRL/RBSM to evaluate and extend our understanding of materials and structures in aerospace structural components that experience extreme combined environments.

Collaboration among the partners is frequent and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and AFRL/RB visitor office spaces are earmarked to directly support the MSSC, as have graduate student tuition waivers.

High-performance hypersonic aircraft are expected to have stringent structural requirements, especially in regard to spatially-tailored aero-thermal structural (STATS) components. These components may include specialty high-performance metal alloys or functionally-graded materials, each specifically designed and manufactured to address the combined thermo-mechanical-aeroacoustic loadings unique to hypersonic applications. Important is the development of efficient methods for quantifying the uncertain responses and the risks of aerostructures. Among other techniques, methods to identify important input uncertainties through sensitivity analyses that allow us to focus on the dominant uncertainties that threaten successful risk-quantified structural design (RQSD) are under development. Our work focuses on carefully selected, small-scale aircraft substructures that can be fully characterized experimentally. These structures are employed in assessing new methodologies for predictive science tying together RQSD, high-fidelity simulations, and novel experimental techniques.

MSSC Team Members

University of Illinois

- Bodony — Acoustic response prediction
- Brandyberry — Uncertainty quantification and risk analysis
- Duarte — GFEA, structural analysis, multiscale analysis
- Geubelle — Multiscale analysis, FEA
- Lambros — Experiments, high strain rates, FGM
- Paulino — FGM, Multiscale analysis, structural analysis
- Sehitoglu — Thermomechanical response, experiments
- Song — Risk, reliability, stochastic events, FEA
- Tortorelli — Sensitivity, optimization

Wright State University

- Penmetsa — Risk, failure probability assessment

University of Texas at San Antonio

- Millwater — System reliability

AFRL/RBSM

- Acoustic experiments, aeroframe design, operating environments, large-scale structural testing

Existing constitutive materials models are generally phenomenological, i.e., they are based on some empirical formulae (e.g., power law) to be fitted to laboratory tests. Phenomenological models rarely work well for advanced materials subjected to extreme conditions, since they usually fail to account for the significant microstructure changes under the extreme environment. Thus novel, physically-based constitutive models are being developed under the MSSC umbrella.

Successfully modeling fatigue in aerospace structures requires detailed knowledge of the various structural and material failure modes across the wide variety of fatigue loadings possible. In parallel to our simulation and RQSD tasks, Center researchers are conducting series of experiments to determine the relative importance of low cycle, high cycle, and fatigue crack growth in materials subjected to thermo-mechanical and aeroacoustic fatigue. Experiments are being performed to understand the interaction between the high stresses associated with thermal loading, superimposed with ultrahigh frequency-induced

Approved for public release; distribution unlimited.

stresses from an aeroacoustic-type loading. In each project, university investigators from UI, WSU, or UTSA are teamed with RBSM personnel to encourage tight relationships between university and government researchers.

The goal of AFRL/RBSM is to (i) plan, manage and conduct research and development programs to analytically predict and enhance structural life and structural response to aerodynamic, aeroacoustic, ground and environmental loads, (ii) develop, demonstrate and transition technologies to extend the life of and/or reduce costs of the aging aircraft fleet; (iii) develop design requirements, guidance and procedures for newly developed aerospace structures technology; (iv) develop methods for analytically predicting and validating the response and life of structures exposed to static and dynamic loading environments; and (v) provide analytical expertise for evaluation and transition of critical structures technologies to the USAF, DoD, and other government agencies and industry. The MSSC provides an active and able source of manpower, technology, and outreach to fulfill these AF and national goals.

Approved for public release; distribution unlimited.

2 Technical Project Progress

A — Response Prediction: Coupled Aero-Thermo-Mechanical-Acoustic Analysis and Simulation

A1 *Design of STATS using Topology Optimization (Glaucio Paulino, Fernando Stump, Larry Byrd) — Completed in 2009*

A2 Generalized FEM Analysis for Transient Simulations (C. Armando Duarte, Patrick O'Hara, Thomas Eason)

A3 Integrated Fluid/Structure Interaction Simulation (Daniel Bodony, Philippe Geubelle, Mahesh Sucheendran, Adam Kuester, Halvorson, Joseph Hollkamp, Robert Gordon)

A4 *Analytical Prediction of Dynamic Response of FGM (Anthony Palazotto, Reid Larson) — Completed in 2008*

A5 Multiphysics, Coupled Analysis of Extreme-Environment Structures (Daniel Bodony, Philippe Geubelle, Christopher Ostoich, S. Michael Spottswood)

A6 *Non-Intrusive Implementation of Multiscale Capabilities in a General Purpose FEA Platform (Thomas Eason, C. Armando Duarte, Jeronymo Pereira) — Completed in 2010*

A7 Multiscale Thermo/Strain Field Coupling (Julia Plews, Thomas Eason, Armando Duarte)

B — Life Prediction: Identification and Definition of Structural Limit States

B1(x) *Failure Analysis of FG Aircraft Components in Combined Environments (Yonggang Huang, Jianliang Xiao, Eric Tuegel) — Redefined in 2007*

B2(x) *Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Martin Ostoja-Starzewski, Ravi Bellur-Ramiswamy, Thomas Eason) — Redefined in 2007*

B1 *Mechanism-Based Cohesive Failure Model for Functionally Graded Aircraft Components and Structures (Eric Tuegel, Glaucio Paulino, Arun Gain) — Completed in 2010*

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Seth Watts, Thomas Eason)

C — Life Prediction: Framework and Methodologies for Risk-quantified Structural Assessment

C1 *Uncertainty/Risk Quantification Methods for STATS (Junho Song, Young Joo Lee, Eric Tuegel) — Completed in 2010*

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Mark Brandyberry, Jason Gruenwald, Mark Haney)

C3 *Risk-Based Design Plots for Aircraft Damage Tolerant Design (Ravi Penmetsa) — Completed*

C4 System Reliability with Correlated Failure Modes (Harry Millwater, Luciano Smith, Daniel Sparkman, David Wieland, Eric Tuegel)

C5 Identifying Structurally Significant Items using Matrix Reanalysis Techniques (Ravi Penmetsa, Bhushan Kable, Vankat Shanmugam, Eric Tuegel)

D — Experimental Discovery and Limit State Characterization

D1 *Experimental Investigation of Thermomechanical Fatigue Failure Modes (Huseyin Sehitoglu, Christos Efstathiou, S. Michael Spottswood) — Completed in 2009*

D2 Development of Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework (Jay Carroll, John Lambros, S. Michael Spottswood)

Approved for public release; distribution unlimited.

D3 Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response (Wael Abuzaid, Huseyin Sehitoglu, S. Michael Spottswood)

D4 Thermomechanical Fatigue of Hastelloy X: Role of Defects (Mallory Casperson, Ravi Chona, John Lambros)

Italic — Concluded projects

Approved for public release; distribution unlimited.

A — Response Prediction: Coupled Aero-Thermo-Mechanical-Acoustic Analysis and Simulation

A2 Generalized FEM Analysis for Transient Simulations (Patrick O'Hara, Armando Duarte, Thomas Eason)

The Generalized Finite Element Method with Global-Local Enrichments (GFEM^{gl}) has been one focus of investigation for the last year. The basic idea of the methodology is to enrich a fixed, coarse mesh with enrichment functions generated through the solution of local boundary value problems selected in the regions of localized behavior, as shown in Figure OHa-1. The local solutions insert knowledge about the localized physics into the global solution space, thus enabling the resolution of very localized thermal spikes on relatively coarse global elements.

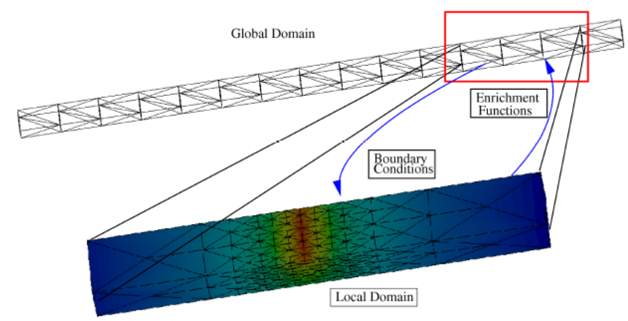


Figure OHa-1: Two-way information transfer in GFEM^{gl}. Boundary conditions are transferred from global to local domains; and enrichment functions are transferred from local to global domain.

The GFEM^{gl} has recently been formulated for, and applied to problems with transient heat transfer. With the expansion of the capabilities of the GFEM^{gl}, the methodology now allows for transient simulations capable of resolving moving, localized thermal spikes, while still utilizing relatively coarse finite element meshes. One significant benefit is that localized features may be resolved in a transient setting without the use of adaptive meshing, or any sort of re-meshing on potentially large and complex models. The second benefit is that with the use of coarse elements, the problem size does not become prohibitively large, as would be the case with high levels of mesh refinement.

Care must be taken when incorporating the GFEM^{gl} into standard time-stepping algorithms, such as the a-method, as there are two possible formulations. In the first formulation the GFEM^{gl} may be plugged directly into the system of equations, as may be found in any FEM textbook. In the second formulation, the equations must be discretized in time first, and then in space. The small difference in the formulation leads to a few subtle differences in the resulting system of equations, but the difference in performance is significant, as shown in Figure OHa-2. With the first formulation, the time-dependent nature of the shape functions is not properly accounted for, whereas the second formulation accounts for the evolving shape

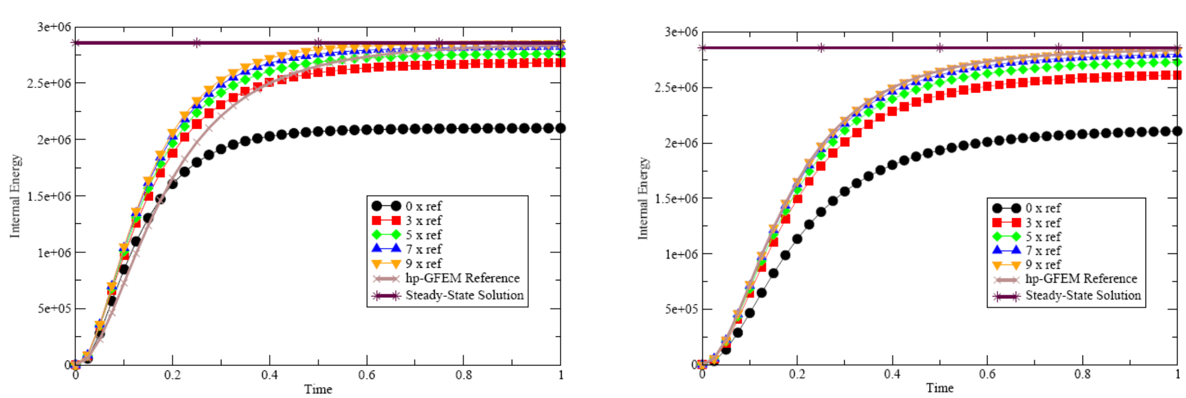


Figure OHa-2: Transient formulation 1 (left) does not account for time-dependent shape functions, and curves do not converge to reference curve. Transient formulation 2 (right) properly accounts for use of time-dependent shape functions, and curves do converge to reference curve.

Approved for public release; distribution unlimited.

functions, and thus generates significantly improved results.

While the global-local enrichments allow for the generation of accurate results on coarse meshes, the hierarchical nature of the enrichments allows for additional gains in computational efficiency. Large portions of the matrices used in the solution process remain unchanged throughout the course of an entire simulation. As such, these portions may be factorized once, and then re-used at each subsequent time-step, in what has been termed the ReAnalysis algorithm. The potential speed-up in CPU time requirements is illustrated in Figure OHa-3.

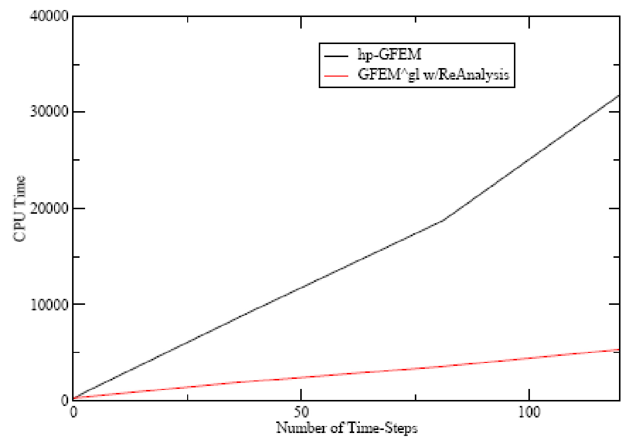


Figure OHa-3: Potential speed-up in CPU time requirements when transient ReAnalysis algorithm is used (red) as compared to standard FEM (black).

A3 Integrated Fluid/Structure Interaction Simulation (Mahesh Sucheendran, Parilo, Phillipe Geubelle, Daniel Bodony, Joseph Hollkamp, Robert Gordon, Timothy Beberniss)

During the past year the focus was on three activities (i) verification of a 3-D parallel, coupled structural-aeroacoustic solver, (ii) development of a 1-D coupled solver to study the accuracy, efficiency of coupling algorithms, and (iii) extension of analytic solution of coupled structural-aeroacoustic interaction of plate in a rectangular duct to include clamped plate boundary conditions and mean flow in the duct.

The verification of the coupled solver is currently in progress. New fluid boundary conditions using the simultaneous approximation term boundary condition were implemented in the fluid domain that makes the coupling numerically stable. The coupled response of a clamped plate in an SEF-like situation is being investigated. Initial results shown in Figure Suc-1 (left) for a 500 Hz, low amplitude aeroacoustic wave impinging on a flat plate shows a multi-frequency beating type of phenomenon in the center displacement of the plate. Numerics of the coupling are being investigated to identify the cause of this beating; the fluid and structural solvers have been individually verified.

Algorithms that will make the 3-D coupled solver more efficient are being investigated with a one-dimensional solver designed to mimic the numerics of the three dimensional solver. The solver was verified using the analytic solution for coupled response of a spring-mass system with a 1-D fluid domain.

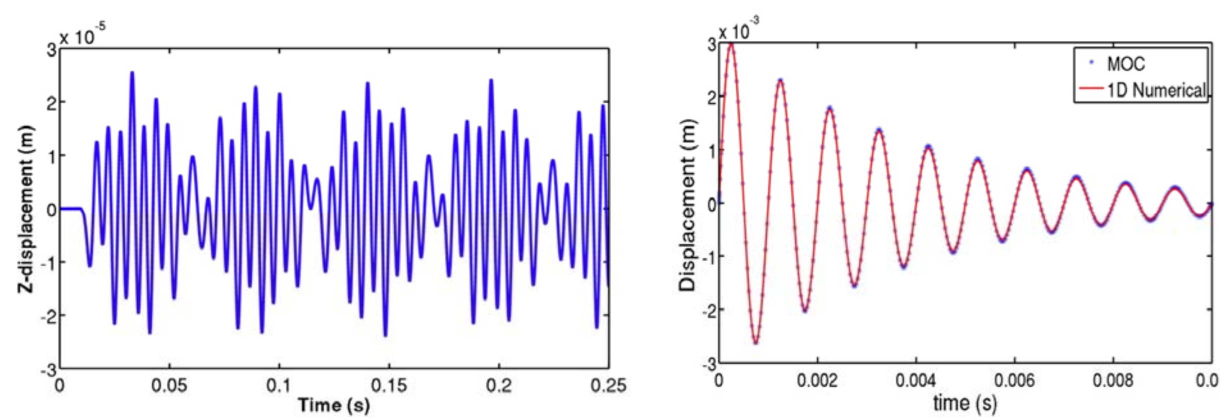


Figure Suc-1: (Left) Center displacement of plate with time for SEF-like conditions; (right) coupled response of a spring-mass system with a 1-D acoustic medium.

Approved for public release; distribution unlimited.

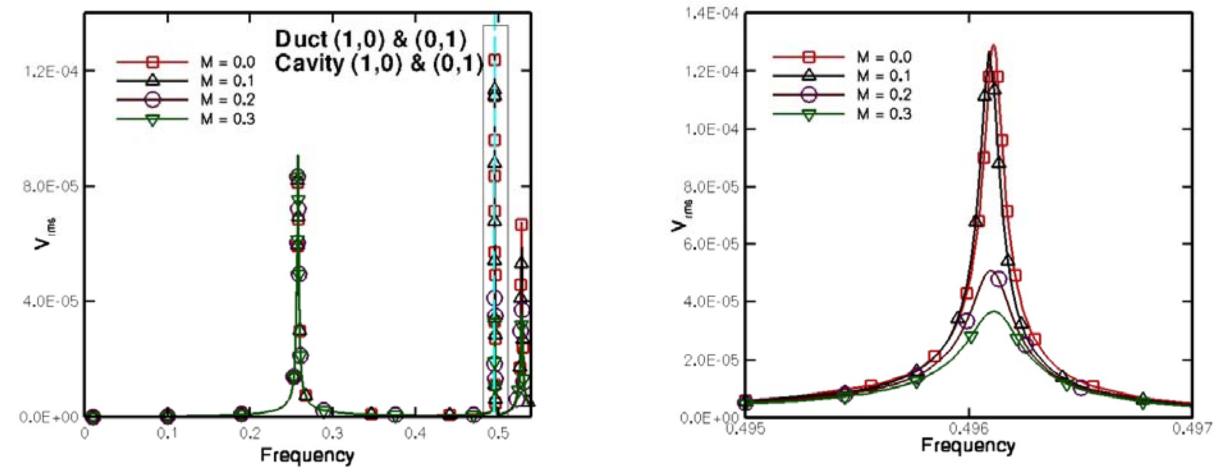


Figure Suc-2: Effect of flow on variation of V_{rms} with frequency for a clamped plate. Zoom-in view of second peak is shown on right.

Figure Suc-1 (right) shows the comparison of the variation of displacement of mass with time calculated using the Method of Characteristic (MOC) solution and using the 1-D solver. Initial results have shown that the coupling algorithm in place is first-order accurate in time. Algorithms are being tested which are second-order accurate and which can sub-cycle the structural solver, i.e., where the (implicit) solid and (explicit) fluid solver can use different time steps.

Finally, the analytical theory for the response of a simply-supported plate in a duct was extended to that for a clamped plate. The theory was also extended to account for the presence of uniform mean flow in the duct. Figure Suc-2 shows the effect of uniform mean flow on variation of integral average of plate velocity with the forcing frequency of the harmonic aeroacoustic load in the duct. It was found that the presence of uniform mean flow in duct acts like a damper to the plate response.

The main focus in the future will be on verifying the 3-D coupled structural-aeroacoustic solver. Various coupling algorithms will be studied using the 1D solver to find the most efficient one. With the verified solver, the effect of uniform mean flow in a SEF-like situation will be studied. Extension of analytic solution to find the effect of radiation into free space on the plate response will also be considered.

A5 Multiphysics, Coupled Analysis of Extreme-Environment Structures (Daniel Bodony, Philippe Geubelle, Christopher Ostoich, S. Michael Spottswood)

The goal of Project A5 is to use a new multiphysics solver capable of providing a “truth model” of the response of a structure in a hypersonic environment to address the level of coupling between the fluid and the structure and its consequences on prediction quality. The new solver makes very few assumptions about the physics of the problem to provide very accurate information, though at a higher computational cost. The highly accurate information given by the solver is increasingly important as the environment of interest progresses further into the hypersonic regime in which experiments are challenging. The solver provides detailed information about this environment and provides accurate data with which reduced order models could be verified.

The first problem to be solved is a validation of the fluid-thermal coupling by reproducing the results of a 1988 hypersonic wind tunnel experiment. The experiment involved a Mach 6.5 flow over a rigid structure representing lightweight body panels of a bowed, metallic thermal protection system. Extensive heat flux, surface pressure, and surface temperature data were recorded against which to compare the data generated by the fluid-thermal solver. The complicated geometry and extreme environment presented a large problem that highlighted areas for improvement in the codes. The second year of Project A5 was dedicated to improving the solver in order to make it more suitable to produce the truth model.

Approved for public release; distribution unlimited.

The fluid solver was used to simulate the fluid only problem of a hypersonic, Mach 6.52 flow over a rigid, isothermal structure. The time to complete the simulation proved to be unacceptable and, so, many improvements to the problem set up as well as the code had to be implemented. Among the changes made were regenerating the 5.6 million grid point mesh, increasing the computational resources and modifying the code for greater efficiency in parallel runs. These changes had an enormous impact, reducing the amount of wall time it took to simulate a fluid particle to traverse the computational domain from 172 days to 2.3 days. Extensive work has been done on the implementation of a time implicit fluid solver to further reduce the time step restriction.

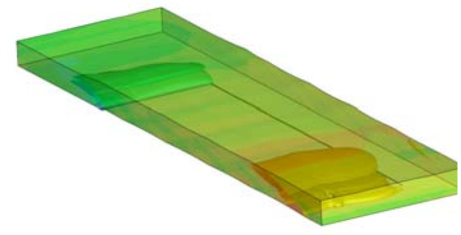


Figure Ost-1: Pressure contours in fluid solution.

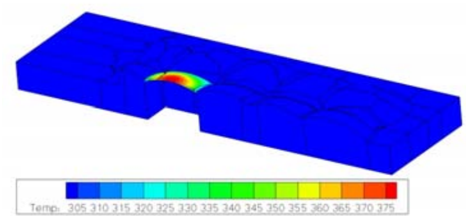


Figure Ost-2: Thermal solution with uniform heat flux on top surface.

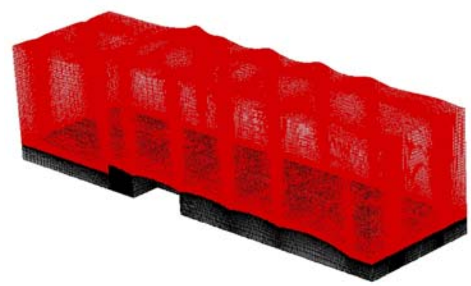


Figure Ost-3: Domain configuration for fluid-thermal validation simulation.

After initial development the thermal finite element solver was verified on a small problem for which an analytical solution was known. However, the first iteration of the code proved to be unsuited for larger, real world problems. Much work was done to improve the efficiency of the thermal solver. Many changes, including the implementation of an iterative rather than a direct linear algebraic solver and modifying much of the code to more efficiently work with sparse matrices, brought the thermal solver to the state where it was suitable to solve large problems. For the 667 thousand-node finite element mesh built for the validation case, the time to solve one time step decreased from several days to 15 seconds.

With both fluid and thermal solvers working well in the uncoupled validation case geometries, the next accomplishment was the fully coupled simulation of a Mach 6.52 flow over the rigid bowed dome model for a limited runtime. The coupled code demonstrated the ability to handle the full validation problem. The complete coupled simulation begins this summer towards validate the thermal-fluid multiphysics solver.

A7 Multiscale Thermo/Strain Field Coupling (Julia Plews, C. Armando Duarte, Thomas Eason)

The availability of a computationally efficient and accurate technique to solve multiphysics, multiscale thermal strain problems is of great importance in the structural design and response prediction of hypersonic flight vehicles. Generalized finite element methods (GFEMs) provide an especially relevant and versatile means for simulations of this nature, enabling the generation of specialized enrichment functions tailored to the problem at hand. In this case, multiscale effects can be approximated by special enrichments derived from small-scale boundary value problems (BVPs) that are then applied to the large-scale problem, leading to the so-called GFEM with global-local enrichments (GFEM^{gl}). Building upon a framework for temperature gradients resulting from transient, sharp thermal loads, steps are being taken to develop a GFEM platform to resolve localized thermo-mechanical stresses and strains while maintaining a coarse, structural-scale mesh.

Much time has been spent over the past year to verify and further explore the behavior of the GFEM^{gl} platform for sharp thermal loadings developed as a part of Project A2, keeping in mind that evaluation of

Approved for public release; distribution unlimited.

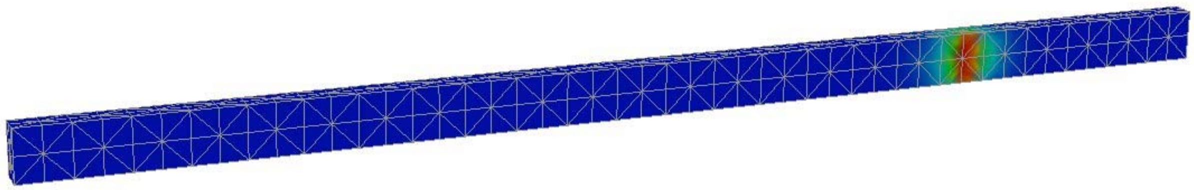


Figure Ple-1: Aluminum beam subjected to laser heating used for global-local analysis; global domain is shown.

this platform is crucial to moving forward with extending functionality to multi-scale thermal strains. The primary focus of this work has been on examining the convergence of the GFEM^{gl} methodology when applied to problems exhibiting sharp thermal features, as questions about the performance and guidelines for use of the method in this context have been a recurring issue in previous review meetings. Figure Ple-1 shows the representative BVP used in the analysis: a three-dimensional aluminum beam subjected to a laser-heating flux. This simple example problem allows the variation of several analysis parameters that are of interest in evaluating the performance of the GFEM^{gl}. For instance, mesh refinements in both the global (structural-scale) and local (small-scale) domains were conducted in order to determine h-convergence behavior with respect to both local and global mesh sizes. Variation in the size of the G-L enrichment region, the portion of the global mesh that is enriched with the solution of the local-scale BVP, was carried out simultaneously to observe its effect on h-convergence rates. As shown in Figure Ple-2, numerical results show a tapering-convergence phenomenon whereby convergence of the GFEM^{gl} is hampered for small sizes of the enrichment region. This discovery has provided crucial insight for moving forward with the method in its application to thermo-mechanical strains, in that such knowledge will assist in determining an optimal size for the global-local enrichment region, and selection of the local problem domain. This study can also guide the formulation of algorithms able to automatically select the size of G-L enrichment regions by the GFEM code.

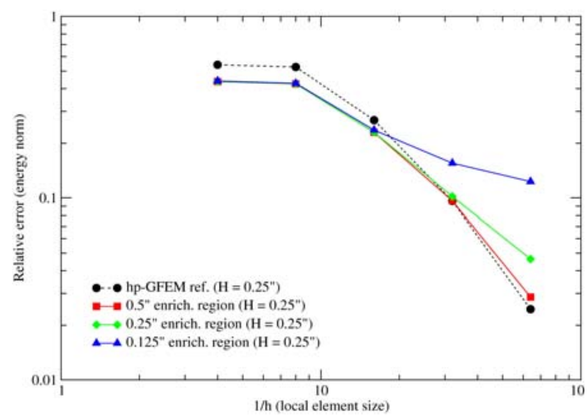


Figure Ple-2: Convergence of GFEM^{gl} with respect to local mesh size for various sizes of global-local enrichment zone. Convergence worsens as enrichment region is reduced while optimal convergence is observed for sufficiently large enrichment regions.

Moving forward, another primary focus of the research is the implementation of a two-solver interface for multi-scale heat transfer problems, combining the benefits of the GFEM^{gl} for transient, sharp thermal loadings with the familiar interface of available FEA software. This implementation will provide both added functionality and accessibility to the GFEM^{gl}, while streamlining the future extension of a two-solver environment to multi-scale thermal strain fields.

Approved for public release; distribution unlimited.

B — Life Prediction: Identification and Definition of Structural Limit States

B1a Mechanism-Based Cohesive Failure Model for Functionally Graded Aircraft Components and Structures (Eric Tuegel, Glaucio Paulino, Arun Gain)

The goal this project is to develop a validated and verified computer code based on potential theory that can handle any loading configuration with mixed-mode fracture. A hybrid scheme was developed to extract cohesive fracture properties of elasto-plastic materials using an inverse numerical analysis and experimentation based on the optical technique of digital image correlation (DIC). Contrary to direct problem, where the material properties (e.g., Young's modulus, Poisson's ratio and fracture properties) are known a priori and the simulation output is obtained the displacement fields; in inverse problem, the displacement fields from the DIC experimentation are utilized and an optimization is performed to obtain the associated material fracture properties. The concepts of the direct and the inverse problem are illustrated in Figure Pau-1.

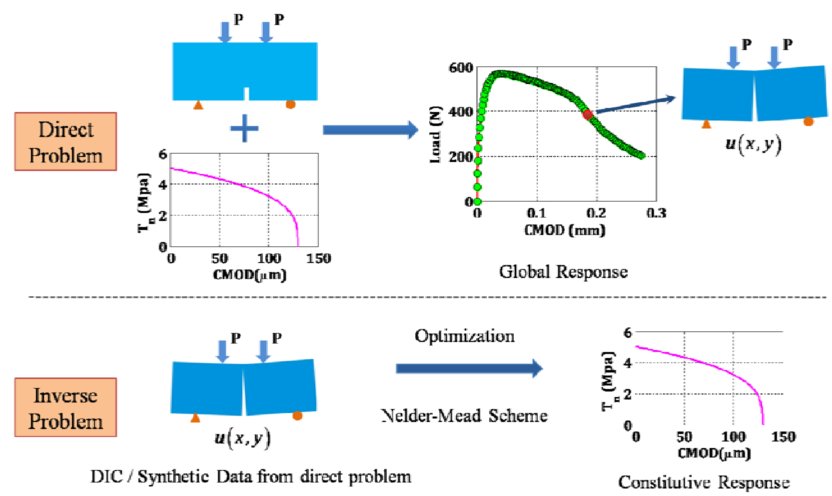


Figure Pau-1: Schematic of direct and inverse problem.

Two schemes for the inverse analysis were proposed – a shape optimization approach, and a parameter optimization for a potential-based cohesive constitutive model, the so-called PPR (Park-Paulino-Roesler) model. The elasto-plastic nature of the bulk elements was modeled using the J2 plasticity theory. Nelder-Mead optimization was used in the inverse analysis scheme to obtain optimized parameters that are later used to obtain the cohesive zone model (fracture model). The framework for the hybrid technique was verified using synthetic displacement field obtained from the direct problem.

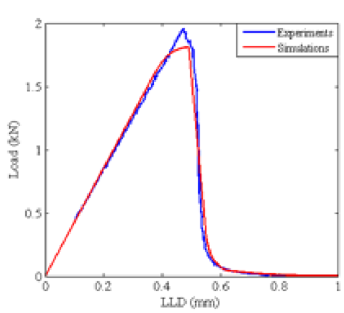


Figure Pau-2: Comparison between experimental and simulation (using Shape optimization scheme) global responses of PMMA specimen.

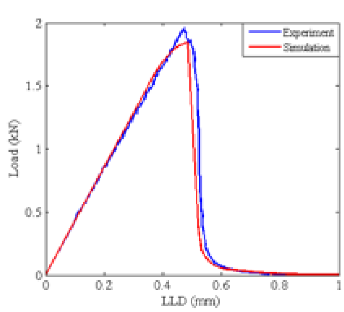


Figure Pau-3: Comparison between experimental and simulation (using Parameter optimization for PPR potential-based CZM scheme) global responses of PMMA specimen.

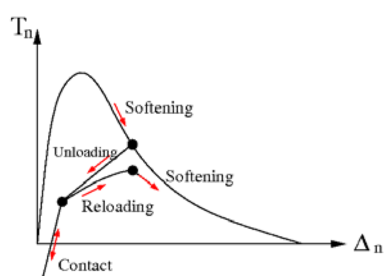


Figure Pau 4. Schematic of cohesive zone based fatigue crack growth models. Model consists of four stages: softening, unloading, reloading and contact conditions.

Approved for public release; distribution unlimited.

To verify the proposed schemes, they were applied to a Poly-methyl-methacrylate (PMMA) quasi-static crack growth experiment. The near tip displacement field obtained experimentally by DIC was used as input to the optimization schemes. The technique successfully predicted the applied load-displacement response of a four-point bend edge cracked fracture specimen. This work was conducted in collaboration with project D2 (Spottswood, Lambros, Carroll). The load versus load line displacement (LLD) plot from the experiments and the direct problem simulations are shown in Figures Pau-2 and Pau-3. Both results are close to each other that give confidence in the extracted CZM.

B1b Mechanism-Based Cohesive Failure Model for Functionally Graded Aircraft Components and Structures (Eric Tuegel, Glaucio Paulino, Kyoungsoo Park)

Fatigue damage is one of major failure phenomena observed in air vehicles. Most fatigue failure investigations have been performed on the basis of linear elastic fracture mechanics like the Paris type relations (e.g. AFGROW) although nonlinear fracture process zone exists ahead of a crack tip. In order to capture nonlinear crack tip behavior, cohesive zone based fatigue crack models have been investigated.

Previous cohesive zone based fatigue crack models possess several limitations. For instance, a model parameter should be free from the number of cycles, because a real structure experiences arbitrary loading amplitude and frequency. The fatigue damage can occur before the cohesive traction reaches the cohesive strength. In order to overcome such limitations and to capture nonlinear fatigue damage processes, a novel cohesive zone based fatigue crack growth model is proposed in this project. The schematics of the cohesive traction-separation relationship are shown in Figure Pau-4. The constitutive model clearly defines four stages during arbitrary fatigue loading: softening, unloading, reloading, and contact. The softening condition is based on the potential-based model (PPR), which has been investigated in conjunction with DIC techniques in this project. For the unloading/reloading conditions two damage measures (k_n, k_t) and two model parameters (CC, CO) are introduced. Two damage measures are associated with the rate of separation and the rate of cohesive traction, which influence the fatigue crack growth rate. Additionally, two model parameters account for crack closure/opening effects, which can be associated with crack face roughness, oxidation of fracture surface, etc. Such crack closure/opening effects lead to nonlinear load versus local crack opening relations, which are generally observed in experiments.

The proposed constitutive model is illustrated by simulating Mode-I problems. First, a unit square domain, fixed at the bottom, is considered. At the top of the domain, the uniform displacement is first applied up to 1.3×10^{-3}. Then, the displacement is unloaded to zero, and it is reloaded up to the complete failure condition. The effect of the rate of traction is shown in Figure Pau-5 (left) – the lower value of k_t leads to further deviation from the original softening curve. The effect of the rate of separation is illustrated in Figure Pau-5 (right) – the higher value of k_n leads to the higher slope in the reloading path. Thus, the higher value of the damage measures represents the higher resistance of the fatigue damage.

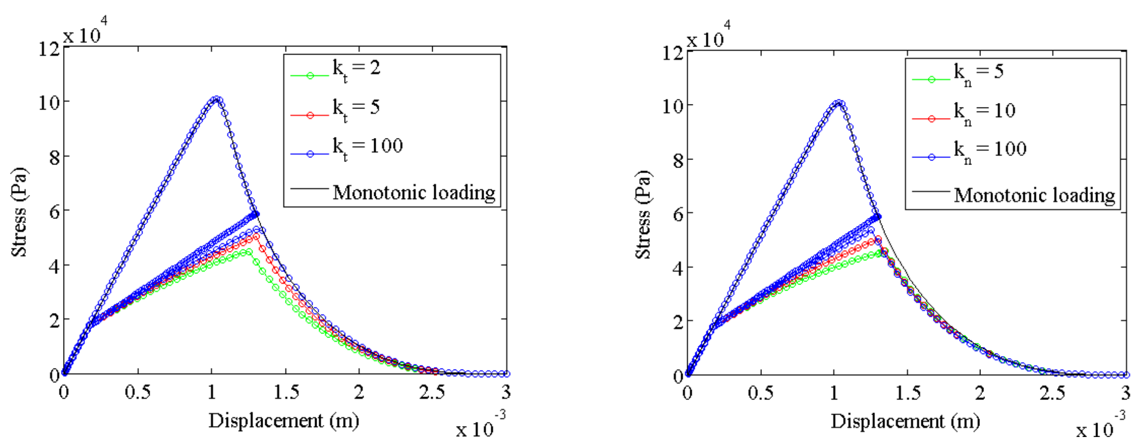


Figure Pau-5: (Left) Effect of rate of traction and (right) effect of rate of separation. Higher values of damage measures (k_n, k_t) lead to higher resistance of fatigue crack growth.

Approved for public release; distribution unlimited.

Next, the double cantilever bean geometry was investigated under constant loading amplitude. The log (ΔK) versus log (da/dN) result is illustrated in Figure Pau-6. The plot clearly demonstrates that the proposed constitutive model captures the stable crack growth region that corresponds to the Paris-type relations.

An attractive feature of the proposed model is that it is completely modular, and can be implemented in commercial software. For instance, it was implemented as a user-defined element subroutine in ABAQUS, and will be included in WARP3D code (developed by the University of Illinois). Furthermore, the model will be extended to study thermomechanical fatigue of Hastelloy X, which is under investigation by Projects D1, D2 and D3.

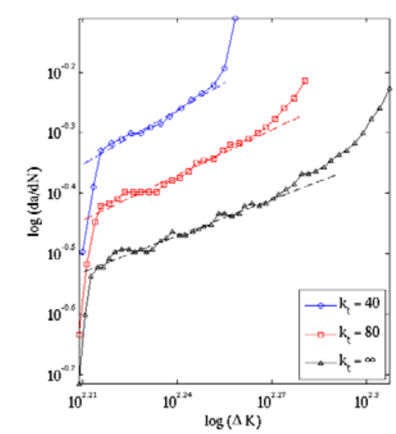


Figure Pau-6: ΔK-da/dN curves in logarithmic scale for DCB test under cyclic loading.

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Seth Watts, Thomas Eason)

This project aims to develop a methodology to optimize functionally graded materials (FGMs) with applications in Spatially Tailored Aero-thermal Structures (STATs). The approach is to quantitatively characterize the microstructure of FGMs, with the goal of developing a statistical mapping of the microstructure's phase morphology to the composite material properties. In conjunction with other ongoing projects, this will enable the ability to predict the properties of novel FGM materials, as well as to optimize FGMs in design applications.

In previous reports we have noted the division of this project into several areas of work, including (i) generating a library of images of candidate FGMs' microstructures, (ii) developing methods to generate quantitative morphological descriptions of the microstructure, and (iii) understanding correlations between morphology and material properties. Previous reports have discussed progress in tasks (i) and (ii); these tasks are now largely complete.

We are now working on the third task, understanding the relationship between the morphological descriptors we are using, and material properties of interest. We have written software that uses finite element analyses to determine the homogenized material properties of virtual FGM specimens. Combined with our software from task (2), we can generate virtual specimens, determine their morphology and properties, and look at relationships between the two.

However, to date we can only do this on specimens created at random, without much control. To fully understand the relationships between morphology and properties, we need to be able to generate specimens with a given morphology. In this way we can observe directly what changes in the morphology have on material properties (versus coincidental changes caused by generating random images).

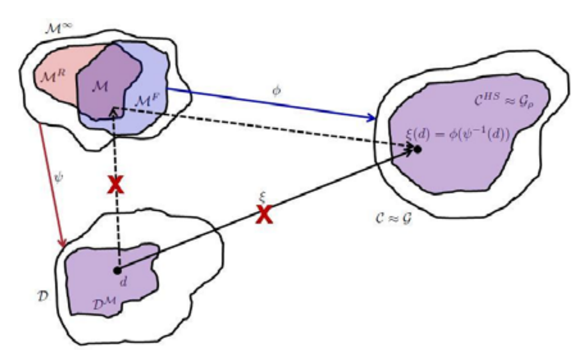


Figure Tor-1: Schematic representation for generation of virtual specimens of given geometry.

Generating virtual specimens with a given morphology is a very hard problem. Figure Tor-1 shows the problem schematically. The set M is (loosely) the set of all possible specimens of a given FGM microstructure. We have a map ψ from M to D, the set of morphological descriptors of M. The morphological descriptors we have described in previous reports are component values of the mapping ψ. We also have a mapping φ from M to the set of material properties C; these are the finite element analyzes previously described. Ideally we would be able to create a mapping ξ from D directly to C, such that we could choose any member of D (a set of descriptors describing some pattern in M) and get its material properties in C directly. However, such a map ξ must necessarily equal the composition $\varphi \circ \psi$ -1, and unfortunately ψ is an uninvertible map.

Under certain conditions, we can ensure that is ψ is at least continuous, allowing us to find a pseudoinverse map ψ ~1, which allows us to map from D to M (not uniquely) and thence to C, allowing us to explore the relationship between morphology and properties as we wish to. In the language of optimization, finding the pseudoinverse map is an inverse problem, and we are approaching this problem with optimization techniques. Our current work is to adapt techniques from several areas of the literature to form a well-posed, tractable inverse problem.

Approved for public release; distribution unlimited.

C — Life Prediction: Framework and Methodologies for Risk-quantified Structural Assessment

C1 Uncertainty/Risk Quantification Methods for STATS (Junho Song, Young Joo Lee, Eric Tuegel)

Aircraft structures are often subjected to risk of progressive failures caused by fatigue cracks growing under repeated loadings. However, due to uncertainties in materials, loadings and mathematical models, and the complex effects of load re-distributions, it is a challenging task to estimate the reliability of aging aircraft structures with the uncertainty in crack growths considered. The goal of this research project is to develop novel system reliability analysis methods for quantifying the likelihood of system-level failure caused by fatigue-induced sequential failures and for identifying critical failure sequences, and to integrate the developed methods with advanced finite element (FE) simulations of aircraft structural systems. The outcomes of the research will provide crucial information for the risk-based life forecasting and condition-based maintenance of aircraft structures.

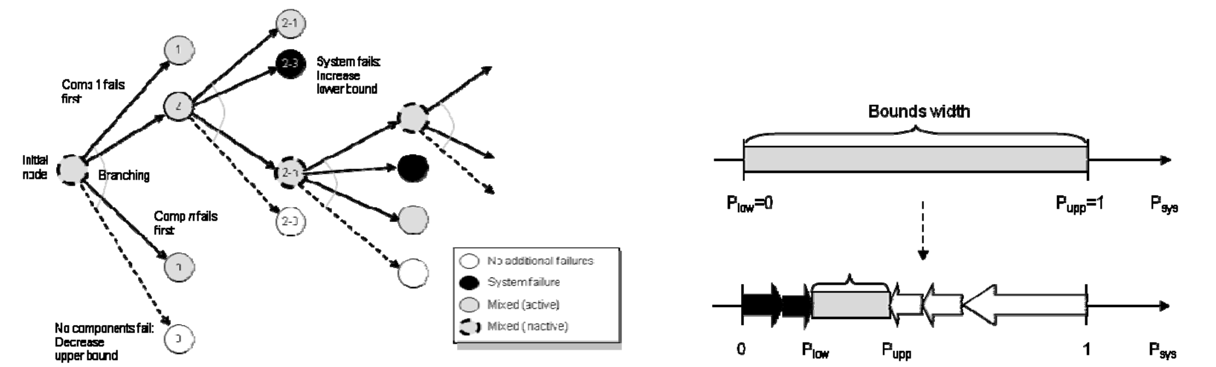


Figure Son-1: Procedure of B^3 method (left) and sequential updating of system failure probability bounds (right).

Toward the development of fatigue system reliability analysis method, we performed a literature review on existing analysis methods for system reliability and structural progressive collapse induced by fatigue. During this review, we identified merits of existing methods as well as further research needs. Based on these findings and discussions with other researchers in MSSC, we developed a new branch and bound method using system reliability bounds, termed as 'B^3 Method.' Figure Son-1 illustrates the procedure of the method (left) and the updating of the bounds (right). The method enables us to estimate the risk of progressive failures accurately while minimizing the costs of structural analysis. In addition, the method can identify most critical failure sequences in the decreasing

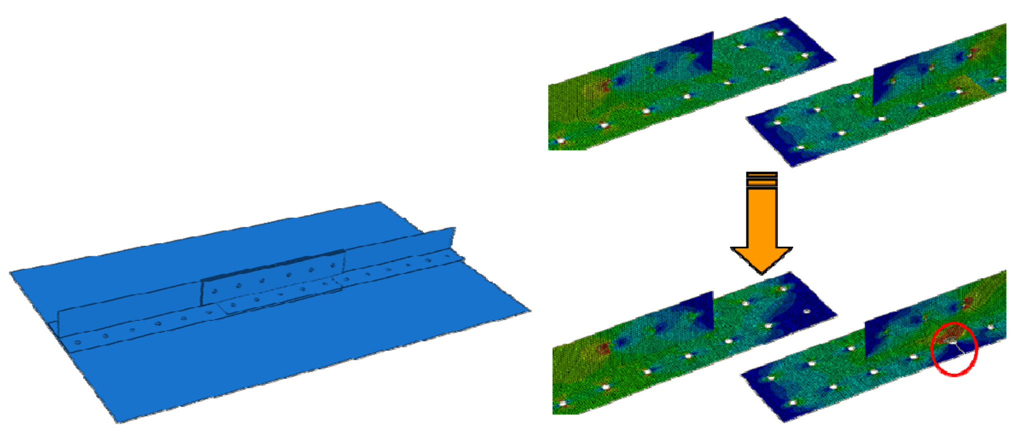


Figure Son-2: Developed longeron FE model for ABAQUS (left) and stress change caused by local cracking failure (red circle) in model (right).

Approved for public release; distribution unlimited.

order of their likelihoods. The B^3 method was successfully demonstrated by a three-dimensional truss structure. A journal paper on this study is currently under review.

In order to test the applicability of the developed method to aircraft structures, a longeron system problem was developed. An FE model of longeron was developed for ABAQUS based on the discussions with researchers in MSSC. A detailed mechanism of fatigue-induced sequential failures of generic aircraft longeron was formulated through collaborations in the center. The developed FE model can simulate fatigue-induced local failures so that the load re-distributions caused by sequential failures can be considered during the B^3 analysis. Figure Son-2 shows the developed FE model (left) and an example of stress re-distribution after a local cracking (red circle) around a fastener hole occurs (right). Currently, the B^3 method is being applied to the longeron problem, and the results will demonstrate the method's applicability to general aircraft structures and help identify further research needs.

The B^3 method is being further developed for quantifying the uncertainty of growing crack length, which is fundamental information for the condition-based maintenance of aircraft. The critical failure sequences identified by the B^3 method will help us quantify the uncertainty of crack propagation using an advanced uncertainty quantification method. Figure Son-3 shows an example of expected outcomes, i.e., the probability distribution (PDF) of crack length as a time-varying function (left) and the PDFs at two different time points (right), which will be helpful to set up a condition-based maintenance scheme as well as risk-based aircraft design.

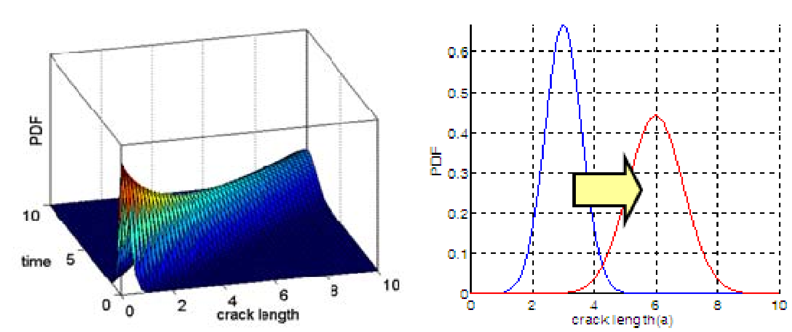


Figure Son-3: Probability density function (PDF) of time-varying crack length (left) and PDFs at two different time points (right).

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Mark Brandyberry, Jason Gruenwald, Mark Haney)

This project involves uncertainty quantification and validation of computer simulations of thin, curved beams (experimental setup shown in Figure Bra-1) under random vibration loads, including nonlinear effects. These beams serve as simple surrogates for thin aircraft panel skins under vibration loads. A validation process is sought for the simulations that incorporate both the system uncertainties in the simulations, as well as experimental uncertainties in the measured data. Experiments are being performed at WPAFB to generate data to be used in the methodology development.

The process uses the developing Reduced Order Clustering Uncertainty Quantification CUQ) methodology developed at Illinois berry, 2008], and experimental data generated by the Air Force. The ROCUQ method allows for uncertainties in simulation input parameters to be efficiently propagated through computationally expensive simulations, through which distributions of output parameters of interest (System Response Quantities, or SRQs) can be created and compared to experimental data (which also has uncertainty associated with it). Progress has been made in creating a Reduced Order Model (ROM) for the


Figure Bra-1. The beam fixed in the testing apparatus and mounted on the electromagnetic shaker. The strain gauges are not shown.

Approved for public release; distribution unlimited.

vibrating beam, a core step in the ROCUQ method, as well as in collaborating with experimentalists on the creation of a series vibration tests.

The Implicit Condensation and Expansion (ICE) [Hollkamp, 2008] method was chosen for the ROM. This method satisfies the requirements of ROCUQ – it is fast running and has the ability to model all of the uncertain parameters in the simulation. The ICE method has also been shown to model nonlinear displacements accurately for similar problems [Hollkamp, 2008]. ICE leverages commercial FEA programs to find a nonlinear equation that has time invariant nonlinear coefficients, which drastically reduces computational expense. In past applications of the ROCUQ methodology, the complexity of the physical system limited which parameters could be chosen as uncertain. For example, a fluid-structure interaction problem was modeled using a T38 wing assembly, but the internal structure of the wing was not known and therefore geometric uncertainties were ignored. The simplicity of the beam experiment allows more uncertainties to be explored. The uncertain parameters that are going to be modeled include: the geometric parameters (width, thickness, radius of curvature); the material properties (Young's modulus, Poisson's ratio, density); the clamped boundary conditions; and the preload, which is the load introduced while fitting a curved beam into the testing apparatus.

In the design of the vibration tests, the collaboration with experimentalists is crucial in early stages to ensure that the test setup and the computational model match, as well as ensuring that data is collected in such a manner as to be useful for comparison to the simulation results. This interaction and the preliminary vibration tests indicated that the clamped boundary conditions and electromagnetic shaker introduced uncertainties that were not initially considered. Depending on the order that the bolts are attached, a preload was introduced that caused an asymmetric static displacement. Also, the electromagnetic shaker created a force on the steel beam. The resulting change in displacement from turning the shaker on due to the electromagnetic force created a significant displacement as shown in Figure Bra-2. From a modeling perspective, the clamped boundary conditions will be modeled as stiff springs. The electromagnetic force is more challenging as needs to be modeled in time and space. In addition, the apparatus has several strain gauges attached that increase the damping of the beam. Preliminary test data is being used to estimate appropriate modal damping values. Finally, there is limited knowledge concerning the probability distributions to be used for the uncertain parameters. Data collected from the 12 experimental samples to be tested will be used to better characterize the distributions. The complete set of vibration tests are expected to be conducted in the summer of 2010.

Upon the completion of the ROM, the ROCUQ methodology will be used to perform a 500-sample uncertainty propagation of the RMS value of the center displacement. The resulting cumulative distribution function(s) (CDF) for the SRQ(s) will be compared to similar CDF(s) from the experimental data. At that point, validation of the computer model will be determined using decision theory. Initial concepts for the decision approach to be used can be found in Nevill [2010].

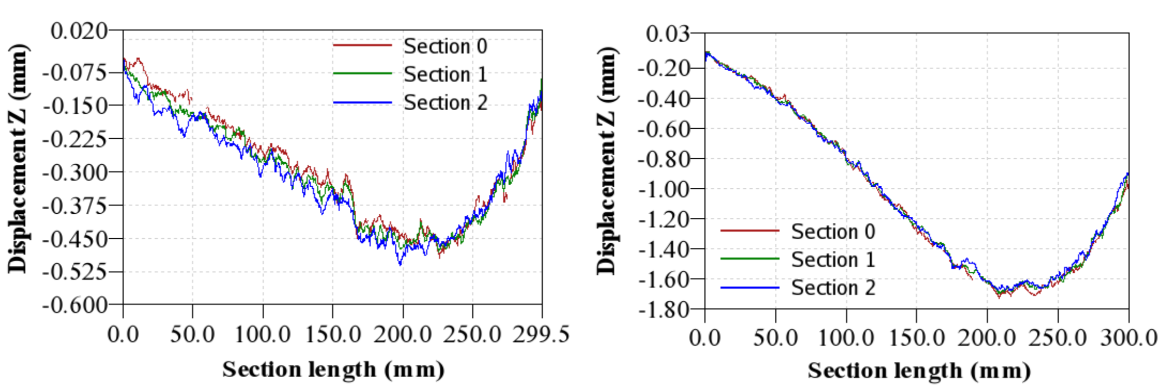


Figure Bra-2. Section displacement of beam (measured three ways) with shaker OFF (left) and ON (right).

Approved for public release; distribution unlimited.

Brandyberry M. D., 2008. “Thermal Problem Solution Using a Surrogate Model Clustering Technique,” Computer Methods in Applied Mechanics and Engineering, Vol. 197(29-32), pp. 2390-2407.

Hollkamp J. J., Gordon, R. W., 2008. “Reduced-order models for nonlinear response prediction: Implicit condensation and expansion.” Journal of Sound and Vibration. Vol 318. pp. 1139-1153.

Nevill D W., 2010. “Methodology for the Validation of Aircraft Simulations in a Mission Scenario Through the Use of a Validation Tree with Uncertainty,” University of Illinois, MS Thesis.

C4 System Reliability with Correlated Failure Modes (Harry Millwater, Luciano Smith, Daniel Sparkman, David Wieland, Eric Tuegel)

New aircraft systems are likely to be constructed of novel materials, operate in extreme environments, and be of limited productions runs. As a result, experience-based methods for determining critical failure locations and failure modes may be lacking. Therefore, a systemic reliability-based methodology was developed to supplement engineering judgment and determine critical locations that are candidates for careful analysis and monitoring during testing and operation. Two filtering have been developed based on a) sampling [1] and b) First Order Reliability Method (FORM).

The sampling based methodology is uses conditional probabilities determined from sampling (Monte Carlo, LHS, or others) to determine the critical limit states. In order to inspire confidence in the results, sampling error is taken into account using methods developed for determining the distribution of the ratio of two random variables. The method was used to determine the critical locations in an example system with failure defined as fatigue cracking in a T-38 upper longeron splice, see Figure Mil-1.

FORM uses a formal pair-wise error metric to filter out noncritical locations in a model. A hierarchical system reliability-based methodology was developed such that fast-running approximation can be used initially with more complex models used selectively. In addition, the FORM method was extended to include Gaussian random fields. The methodology was successfully applied to an exhaust manifold with temperature defined as a random field, see Figures Mil-2 and Mil-3.

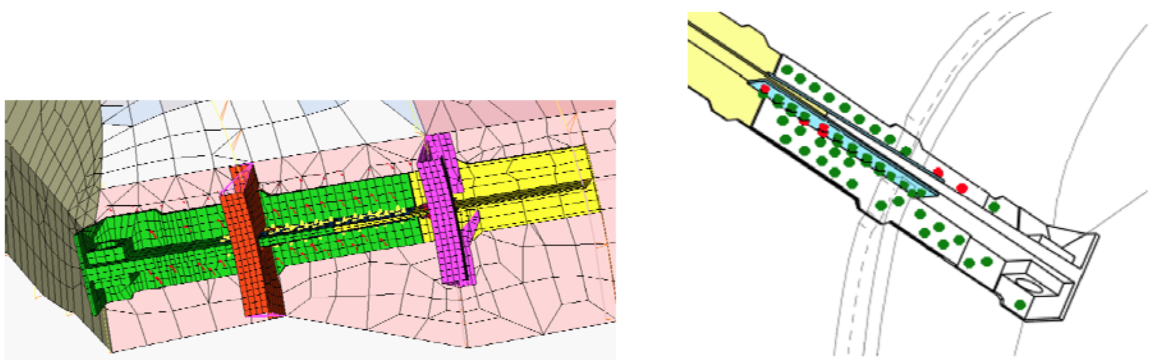


Figure Mil-1: Filtering analysis using sampling on T-38 longeron: finite element model on the left, critical limit locations in red on the right.

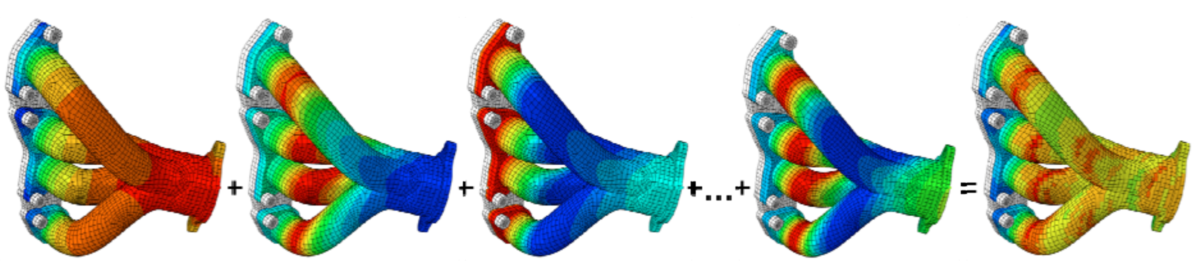


Figure Mil-2: Exhaust manifold mode shapes of random temperature field.

Approved for public release; distribution unlimited.

C5 Identifying Structurally Significant Items using Matrix Reanalysis Techniques (Ravi Penmetsa, Bhushan Kable, Vankat Shanmugam, Eric Tuegel)

In the recent years Cohesive Zone Models (CZM) have gained increasing popularity for modeling the fracture process and also in other applications like composite delamination, solder failures in circuits, etc. This can be attributed to the ability of the CZM to adapt to the nonlinearities in the process it represents by adjusting the model parameters. These parameters that are selected to represent the material behavior in the vicinity of the crack or a damage zone are non-deterministic in nature resulting in random fracture strength estimates. Currently there are no standardized tests for measuring the CZM parameters and their random scatter. Numerous researchers in the literature suggest values for the CZM parameters based on their experience from limited test data. Traditionally fracture toughness is determined through coupon tests for any material system that is being analyzed using Linear Elastic Fracture Mechanics (LEFM) to determine the fracture strength of a specimen. Since data for fracture toughness is available, this research is aimed at determining the probability density functions for the cohesive zone parameters that would give the same scatter in fracture strength as that obtained from the test statistics. Correlations between the model parameters were introduced to improve the accuracy of the fracture strength PDF. A finite width cracked plate is the test case to demonstrate the process. Figure Pen-1 shows the flow chart that identifies all the steps involved in calibrating the probabilistic CZM.

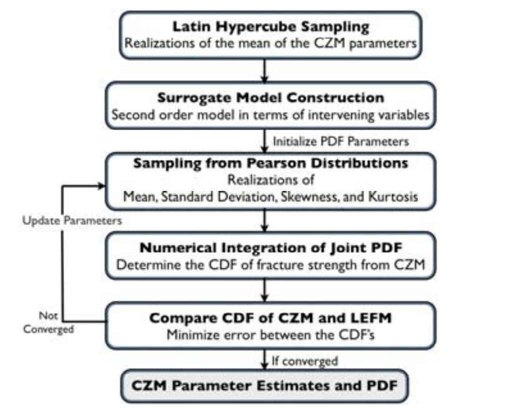


Figure Pen-1: Flow chart for determining CZM parameters and PDF's

In this research, bi-linear and PPR cohesive zone models were used to demonstrate the process and their cumulative distribution functions are shown in Figure Pen-2. Clearly both the models were able to capture the test data accurately. Another key finding of this research is the normalized fracture strength PDF. This normalized PDF represents the scatter in material strength and can be scaled to determine strength at any crack length. Two different half-crack lengths, 1 inch and 2 inch, were selected to demonstrate this feature. For both 1 inch and 2 inch half-crack lengths the normalized PDF's are shown in Figure Pen-3. Even though these distributions are visually the same, two analytical measures were used to ensure that they represent the same level of uncertainty. One was the Bhattacharya distance and the other was the entropy measure. Both the measures indicate that these distributions represent the same level of uncertainty. Therefore, this proves that the material randomness is independent of the geometric variables and can be calibrated separately. This finding will enable construction of a nomograph for rapid risk assessment, which will be the focus of next year's effort.

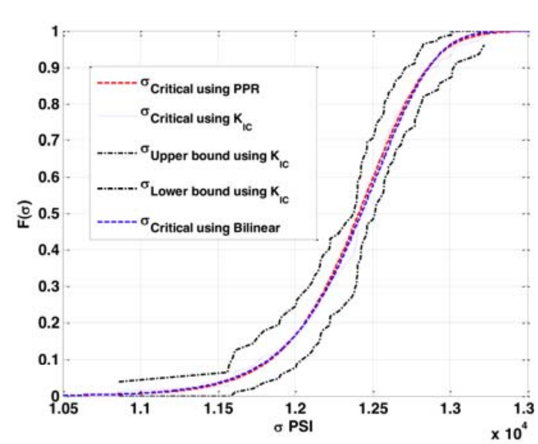


Figure Pen-2: Residual strength CDF comparison

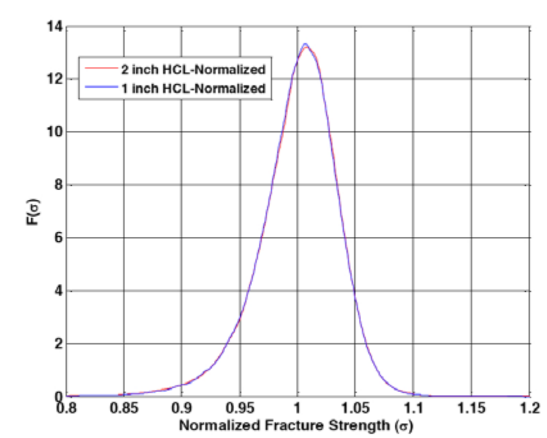


Figure Pen-3: Normalized fracture strength PDF's for two half-crack lengths

Approved for public release; distribution unlimited.

D — Experimental Discovery and Limit State Characterization

D2 Development of Novel Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework (Jay Carroll, John Lambros, S. Michael Spottswood, Ravi Chona, Mallory Casperson, Wael Abuzaid, Huseyin Sehitoglu)

The objectives of this project are twofold: first, techniques are being developed for high temperature thermomechanical fatigue experimentation; second, grain level material behavior is being studied in crack growth fatigue. Throughout the past year, this project has focused on investigating fatigue crack growth of Hastelloy X at the microstructural level using digital image correlation (DIC). Predicting the behavior of advanced aero-thermal structures will require physics-based fatigue models as opposed to the inadequate phenomenological models currently in use. Because fatigue damage initiates and accumulates at the grain level, microscale techniques that have sub-grain level resolution will be needed to develop and validate these physics-based fatigue models.

Table Car-1: DIC resolution is dependent on magnification.

Mag	Field of View (μm)	Scale (μm/pix)	Subset Size at 101 pix (μm)
1.6x	4400 x 3300	2.72	275
3.2x	2200 x 1600	1.36	137
10x	700 x 500	0.44	44
14x	530 x 400	0.31	33
50x	140 x 100	0.087	8.7

To this end, grain level measurement techniques were developed to investigate the accumulation of strain in fatigue crack growth. Because the spatial resolution of DIC is determined by the DIC subset size, increased magnification allows for higher resolution measurements as shown in Table Car-1. The optical magnification of in situ experiments in the load frame is limited to 14x that results in a 101 x 101 pixel subset size of 33 μm. This subset size, roughly one-third the size of the 90 μm average grain diameter of Hastelloy X, has been seen to be too large for grain level measurements. Therefore an optical microscope was used to obtain an ex situ magnification of 50x, allowing for a subset size of 8.7 μm. This much smaller 50x subset size is roughly one-tenth the grain diameter of Hastelloy X, giving the sub-grain level spatial resolution that is necessary for grain level investigations of fatigue.

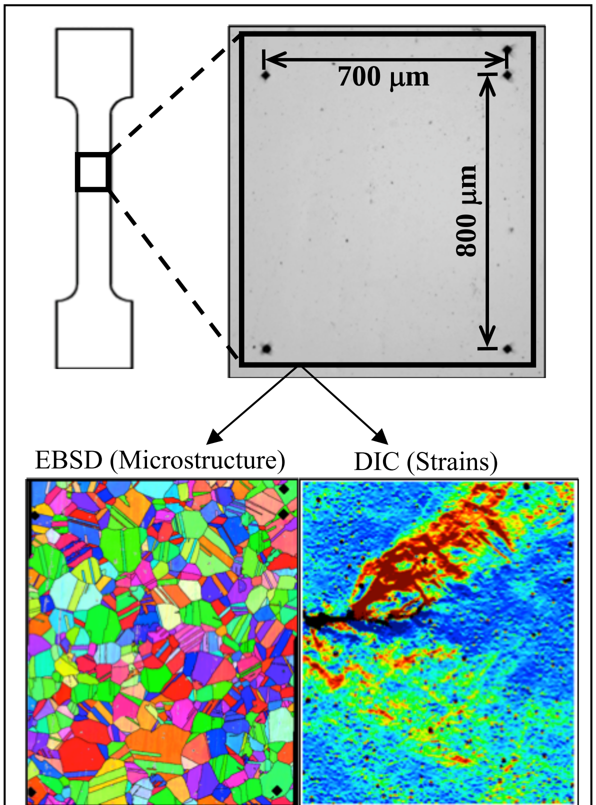


Figure Car-1: DIC strain measurements are linked to EBSD microstructure measurements. Alignment is accomplished using Vickers indentation marks.

Because the field of view at 50x magnification is only 140 x 100 μm (see Table Car-1), an array of 112 images was captured to cover the entire region of interest (700 x 800 μm as shown in Figure Car-1). This allowed high resolution measurements to be acquired over the entire region of interest. An ex situ technique was developed to perform DIC on these images, and to relate the resulting sub-grain level strain measurements to microstructural geometry and orientation, of the same material region, obtained from electron backscatter diffraction (EBSD) as shown in Figure Car-1.

Approved for public release; distribution unlimited.

The ex situ DIC procedure consists of six steps which are meant to ensure that high resolution DIC strain field maps can be precisely combined with comparable resolution microstructural information. These six steps are: (1) placing fiducial markers on the sample to be used for spatial alignment of the various datasets to be collected; (2) gathering microstructural information through EBSD measurements; (3) applying a speckle pattern to the specimen and capturing reference images in the optical microscope; (4) loading the specimen (mechanically, thermally, etc.) such that permanent deformation is achieved, and capturing images of the deformed specimen; (5) stitching the images and performing DIC; (6) aligning the DIC strain field from step (5) with the microstructure obtained with EBSD from step (2) using the fiducial marks placed in step (1).

Fatigue crack growth was investigated at the grain level using the newly-developed ex situ technique. The results from one of these experiments will be discussed here. A single edge notch tension specimen with dimensions of 50 x 9 x 3 mm and a 1 mm long notch was used. After placing markers on the specimen, obtaining microstructural measurements in the region of interest, and applying a speckle pattern, the specimen was fatigue loaded to initiate a crack from a starter notch. The crack was grown under an approximately constant stress intensity factor loading ($\Delta K = 18$ MPa$\sqrt{m}$, R = 0.1), and the specimen was removed from the load frame for high-resolution optical microscopy at intervals of roughly every 0.5 mm of fatigue crack growth. Full field measurements of fatigue strain accumulation were obtained by correlating these images of the specimen with images captured before the start of fatigue loading. Fatigue strain accumulation within the region of interest was measured as the crack tip approached and passed through the region of interest. The techniques developed in this project allowed EBSD microstructure maps to then be precisely aligned with strain fields. In Figure Car-2, grain boundaries are overlaid on top of the strain field when the crack is midway through the region of interest. Only half of the region of interest is shown here for clarity—note the three indentation marks at the top of the plot in Figure Car-2 (a). A closer examination of one region of this overlaid field, shown in Figure Car-2 (b), reveals two strain localizations. By comparing these strain localizations to the grain orientation map in Figure Car-2 (c), it is discovered that these strain localizations lie on a twin and a grain boundary. An investigation of the roles of twins and grain boundaries on fatigue strain accumulation near a growing fatigue crack is currently underway.

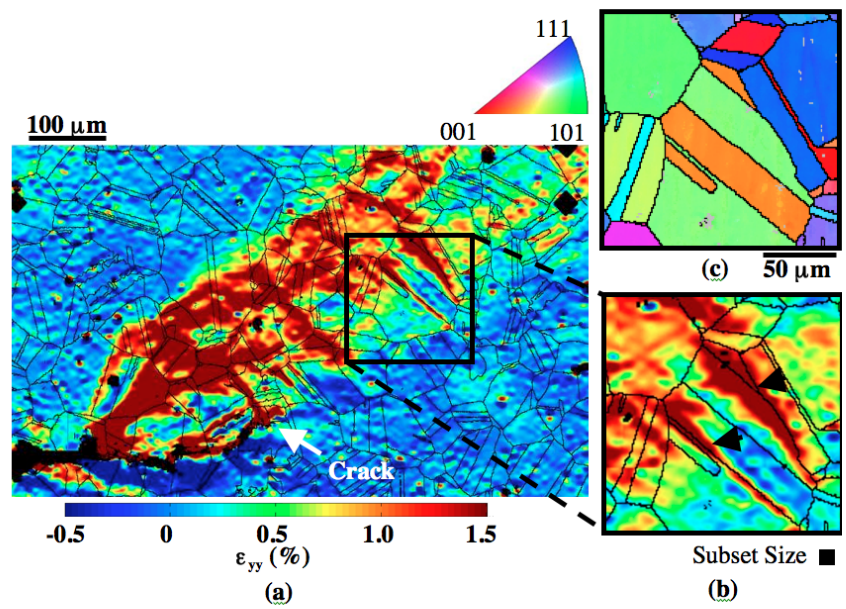


Figure Car-2: (a) Grain boundaries obtained using EBSD are overlaid onto the DIC strain field perpendicular to the crack line. (b) A closer look at the outlined region shows two strain localizations. (c) Using EBSD measurements, it is discovered that the strain localizations observed in (b) lie on a twin boundary and a grain boundary.

Finally, fatigue strain accumulation over time can be observed with this technique. As alluded to earlier, the specimen was removed from the load frame and imaged at several crack length intervals. Accumulated residual (plastic) strain fields are shown for four of these crack lengths in Figure Car-3. In this figure, strain fields C, D, E, and F show the vertical strain component (the dominant strain here) in the region of interest when the crack length, a, is 2.6, 3.0, 3.4, and 3.7 mm, respectively. As the crack ap-

Approved for public release; distribution unlimited.

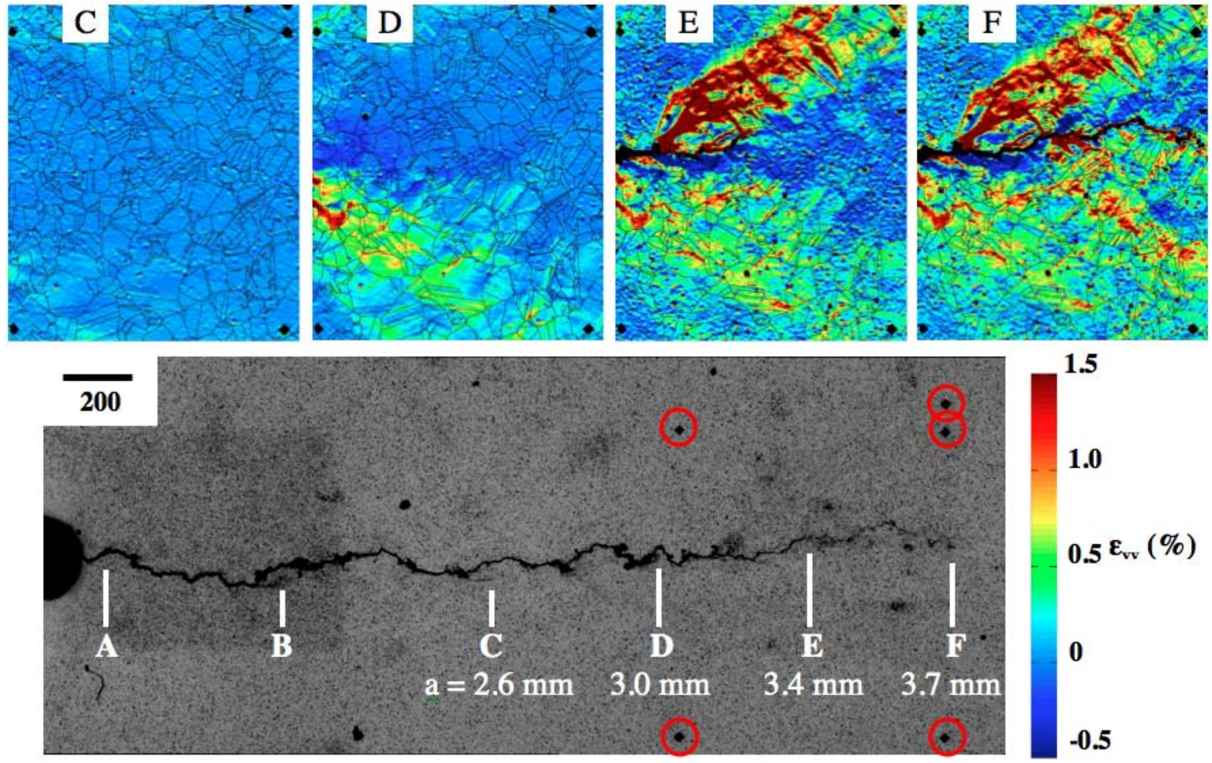


Figure Car-3: Evolution of the strain field perpendicular to the crack line as the crack tip approaches and moves through the region of interest. The crack generates an inhomogeneous strain field that varies with the local microstructure.

proaches and grows through the region of interest, it generates two angled lobes of increased strain ahead of the crack tip, and it leaves behind a wake of plastically deformed material. Many strain localizations can be observed in these high strain regions both ahead of and behind the crack tip. By relating these localizations to the microstructure of the specimen, we hope to gain insight into the process of fatigue damage accumulation and resulting fatigue crack growth.

D3 Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response (Wael Abuzaid, Huseyin Sehitoglu, Ravi Chona, Jay Carroll, Mallory Casperson, John Lambros)

Depending on the relative magnitudes of cyclic mechanical and thermal loading, different response regimes are possible (e.g. Elastic thermo-mechanical fatigue, Shakedown, Ratcheting, etc.). The focus of this project is to mentally investigate; using multiscale full field techniques such as digital image correlation (DIC) and Electron Backscatter Diffraction (EBSD), both the thermo-mechanical fatigue (TMF) response and the thermal ratcheting response of Hastelloy X. DIC will

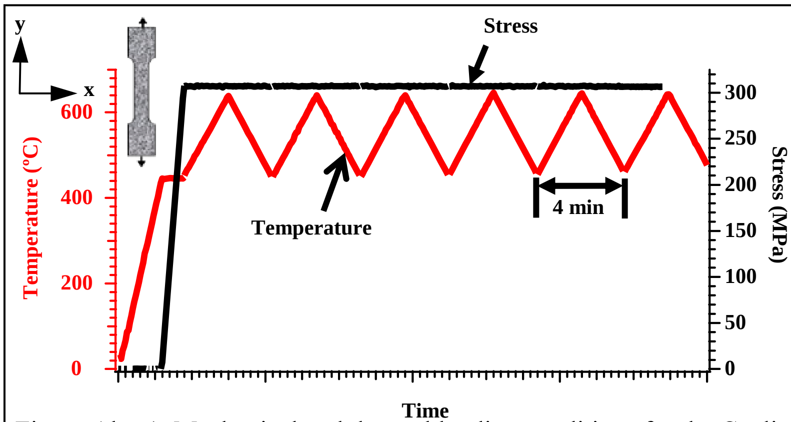


Figure Abu-1: Mechanical and thermal loading conditions for the Cyclic Creep experiment. Stress held constant through out the experiment at 306 MPa (1.25 x σ_{yield} @ 650 ºC). Temperature was cycled between 450-650 ºC.

Approved for public release; distribution unlimited.

be used to observe the evolution of damage in situ at the macroscale and ex situ at the grain level. This work will aid modeling efforts, and can be used to validate simulations performed in other related projects.

Specific techniques for full field deformation measurements at high temperatures have been previously developed in this project (using DIC). Challenges related to initial surface oxidation and sample glowing (above 650 ºC) have been successfully addressed for isothermal loading conditions. This allowed for monotonic tension experiments at temperatures up to 1,000 ºC. The same techniques were also applicable for measurements that involve thermal cycling up to 650 ºC. This has been validated by measuring the thermal expansion coefficient of Hastelloy X, where the values obtained were found to be in good agreement with literature values.

Our earliest study of the cyclic thermomechanical loading response of Hastelloy involved one TMF experimental configuration in which temperature was cycled while load was kept constant, and one configuration where both load and temperature were cycled in phase, producing a range of response depending on load and temperature. In the first TMF experiment, a dog bone specimen was held at a constant load, a little above the yield value at 450°C, while cycling the temperature between 450-650 ºC (as shown in the combined loading history plot of Figure Abu-1). In this cyclic creep experiment, in situ DIC was used to measure strain evolution. Figure Abu-2a shows the net vertical strain (e_{yy}) accumulation, calculated from DIC average fields, versus time. The first portion of strain increase is a thermal part induced by heating the sample from room temperature to 450 ºC. Once at that point, mechanically loading the specimen to the constant stress level of 306 MPa induced mechanical strains, both elastic and plastic, since the yield point of the material was exceeded. In the first temperature cycle (450-650 ºC), further plastic deformation took place due to change in material properties while increasing the temperature (additional mechani-

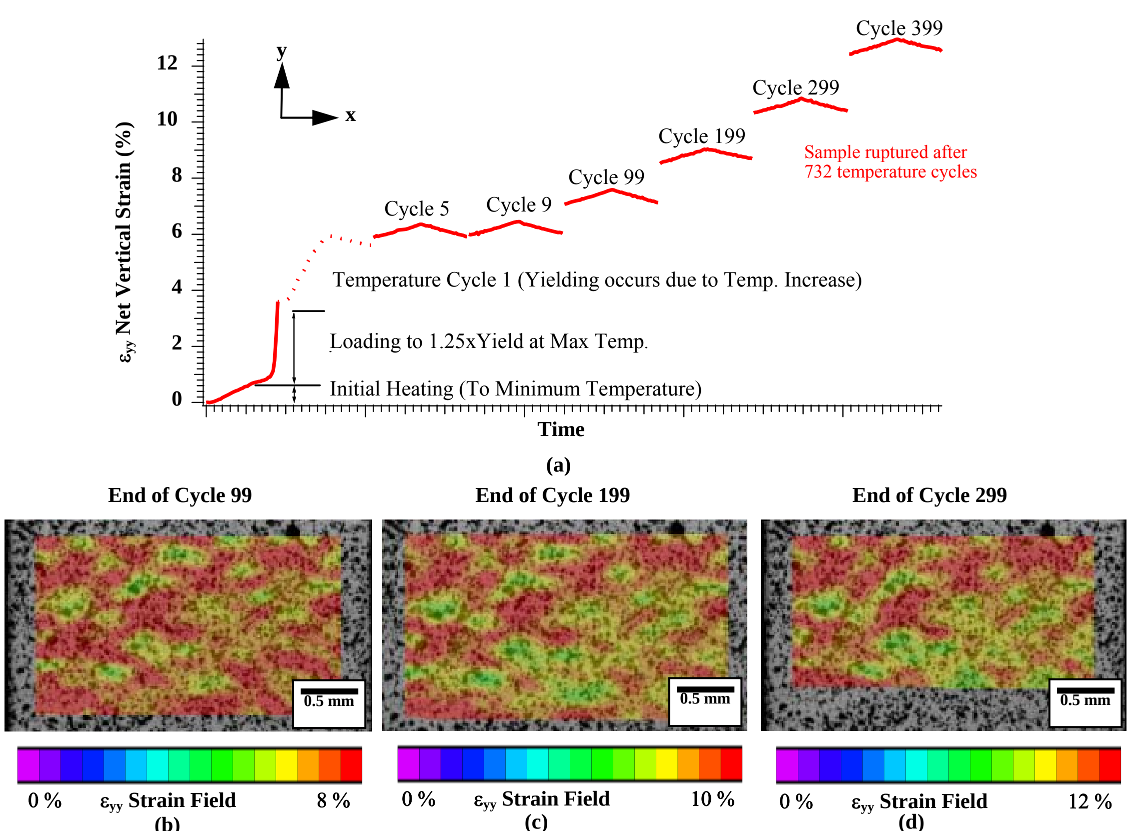


Figure Abu-2: (a) Net vertical strains versus time (Strains from DIC average fields). (b), (c) and (d), Full field vertical strains at the end of cycles 99, 199 and 299 respectively. Notice the localized response and strain buildup in the same locations with increased number of cycles.

Approved for public release; distribution unlimited.

cal strains). In each of the cycles beyond the first cycle, the net strain increased while increasing the temperature and decreased in the second half of the cycle. Over time however, the net residual strain increased. This accumulation of mechanical strains is creep dominated.

The full field contour plots of the net vertical strain (Figure Abu-2b-d) show a localized response by the development of bands of high strains. Also with increasing cycles we note from these contour plots, that strain builds up and intensifies around the same bands. The full field measurements from DIC can also be utilized to construct strain histograms, i.e., the frequency of occurrence of a particular strain level in a DIC image, as shown in Figure Abu-3. The increased width of these histograms with time is clear evidence of an increased level of heterogeneity developing in the material as strain evolves.

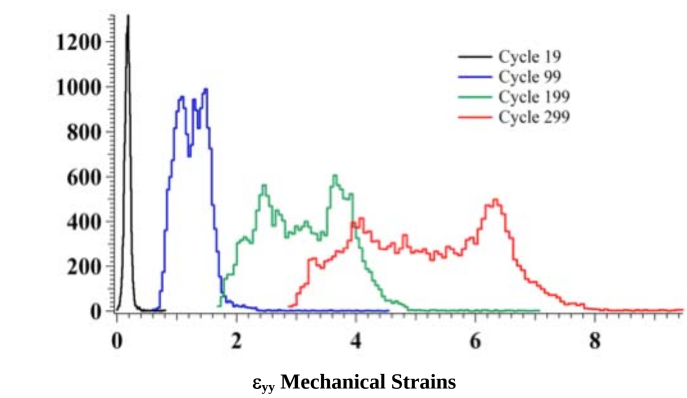


Figure Abu-3: Strain histograms of the vertical strains (generated from full field DIC fields). Notice the increasing width of the histogram with cycle number. This indicates an increased level of heterogeneity developing in the region of interest.

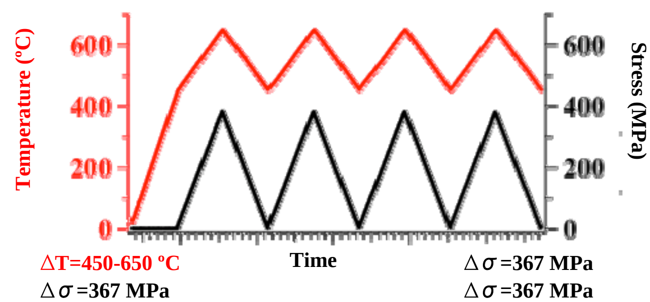


Figure Abu-4: Mechanical and thermal loading conditions for the TMF experiment. Stress was cycled between 0-367 MPa (1.5 x σ_{yield} @ 650 ºC). Temperature was cycled between 450-650 ºC.

The second TMF experiment was designed to probe the entire range of material response – from elastic fatigue, to shakedown, to TMF, up to thermal ratcheting – both load and temperature were cycled simultaneously. Similar to the previous case, the sample was first heated to the minimum temperature level of 450 ºC while keeping the load at zero. Once at 450°C, both load and temperature were cycled in-phase for the specified number of cycles. Using one specimen, a total of 20 TMF cycles were applied at five different stress ranges (0-122, 184, 245, 306 and 367 MPa) and a constant temperature range between 450-650 ºC. Figure Abu-4 shows the actual loading conditions at the fifth stress range, which is representative of ratcheting.

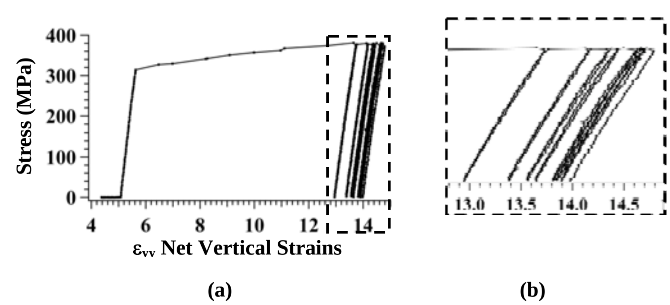


Figure Abu-5: (a) Stress versus net vertical strains for the first 8 TMF cycles (Strains from DIC average fields). (b) A portion of (a) enlarged to show the details of the stress strains response of cycles 2-8. Notice the continuous accumulation of strain after each and every cycle.

In situ DIC was again used to measure the cyclic stress-strain behavior of the material at each of the 5 cases. Depending on the stress range, different deformation regimes were observed. For the first and second stress ranges (0-122 and 0-184 MPa), the material response was elastic (s_{yield} @ 650 ºC=244 MPa). In the third stress range, the material re-

Approved for public release; distribution unlimited.

sponse was characterized by yielding in the first cycle followed by elastic behavior or shakedown. For the last two cases, a ratcheting response was observed. Figure Abu-5 clearly shows a continuous accumulation of strain after each and every cycle at the 5th stress range.

The uniqueness of the two TMF experiments presented here is that all deformation measurements were performed on a full field basis using DIC. The additional information available from such measurements is useful in any modeling efforts. For example, the maximum local strain, as opposed to the mean strain only, in the material (viewed from strain contour plots or histograms) is likely an important variable when trying to predict fatigue failure. Also, the location of such strain localizations can be related to microstructural features (for example from Electron Backscatter Diffraction as illustrated in Project D2), thus providing a quantitative methodology for assessing the effect of different microstructural heterogeneities (e.g. grain size, grain boundaries, etc.) on the measured material response. Such quantitative analysis of the TMF deformation regimes will be the focus of future work on this project.

D4 Thermomechanical Fatigue of Hastelloy X: Role of Defects (Mallory Casperson, John Lambros, Ravi Chona, Jay Carroll, Wael Abuzaid, Huseyin Sehitoglu)

The objective of this project, which forms a direct continuation of Project D2, centers on extending the techniques and measurements made in D2 at room temperature to higher temperatures – up to about 1,000°C. Continuity of the projects has been ensured by the overlap of the two students working on these projects; Jay Carroll and Mallory Casperson. The approach in D4 involves studying aspects of fatigue crack growth in Hastelloy X, a nickel-based superalloy, under a variety of conditions, and relating fatigue crack growth to microstructural features through the methodologies developed in Projects D2 and D3.

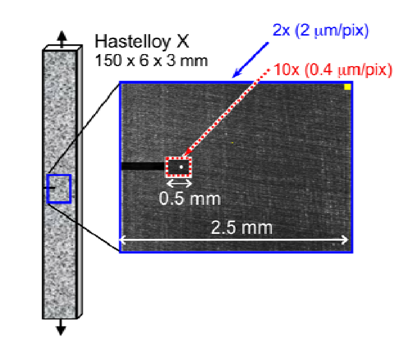


Figure Cas-1: Specimen geometry and fields of view for DIC experiments.

Hastelloy X has been extensively used in the past for high temperature applications. However, less is known about its thermomechanical fatigue response compared to other structural metals. The starting point for this D4 effort was to investigate the effects of crack closure on fatigue crack growth in Hastelloy X, and specifically how temperature affects the development of crack closure. It is unclear at this stage whether during fatigue crack growth at elevated temperatures crack closure is amplified or suppressed. The specimens used in this work were uniaxial tension edge cracked specimens similar to those used in D2. Figure Cas-1 shows the specimen loading geometry. The specimen was polished and painted with a speckle pattern of high temperature paint in order to create a pattern adequate for the use of the optical technique of Digital Image Correlation (DIC) at elevated temperatures. Figure Cas-1 also shows the field-of-view of images taken at two different magnifications: macroscale 2x (2 microns/pixel) and microscale 10x (400 nm/pixel). Since we wish to study crack closure, the stress ratio, R, was maintained at 0.05 so as to facilitate the development of closure. With the crack grown to a distance of about 2.4 mm (about 200,000 cycles) from the edge of the specimen, fatigue loading was halted and the specimen was subjected to several single cycles at the same load amplitude, but at a reduced frequency (0.125 Hz instead of 2 Hz). During these measurement cycles images were captured throughout loading. After performing the measurement cycles at room temperature and at both magnifications, the sample was heated, by induction heating, to temperatures of 250°C, 350°C, 450°C, and 550°C, after each of which an additional measurement loading cycle was applied, with images being taken this time only at

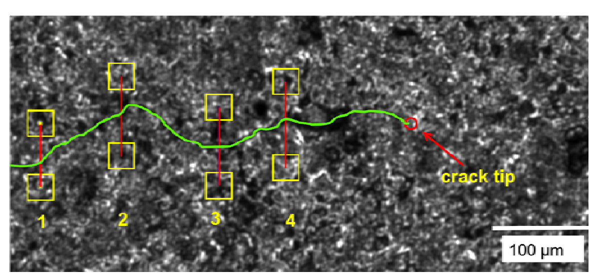


Figure Cas-2: Image at 10x showing location of DIC displacement gauges with respect to the crack tip.

Approved for public release; distribution unlimited.

2x.

Figure Cas-2 shows an image taken during the measurement cycle at room temperature and peak load at 10x (400 nm/pixel) behind the crack tip. The yellow boxes seen are locations where DIC allows us to measure crack face opening. Relating this opening with load, Figure Cas-3, shows that closure is evident for load up to about 70% of peak load. The consequence of this is shielding of the crack tip by a reduction in the local effective stress intensity factor (SIF) over that which is nominally applied at the far field. The 2x measurements allow for a direct measurement of the local SIF, while the applied loading can furnish the theoretical value of the applied SIF, both shown in Figure D4_4a. The early part of this SIF plot clearly illustrates once again, but this time from the macroscale, the substantial amount of crack tip shielding arising form plasticity induced closure.

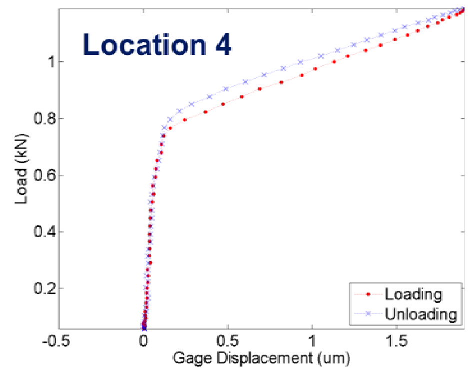
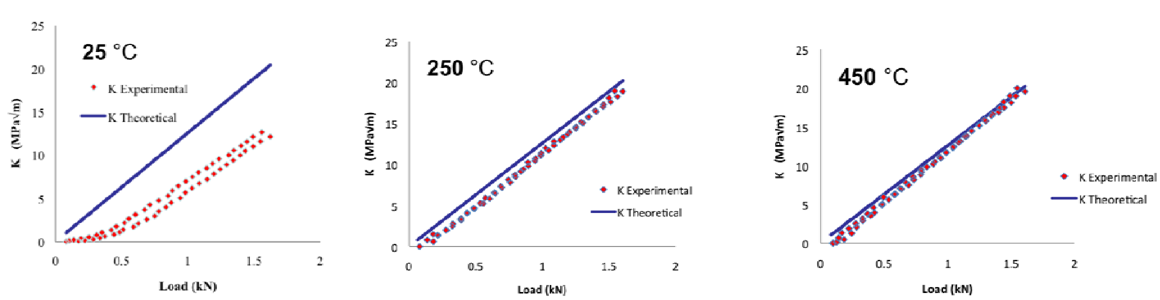


Figure Cas-3: Applied loads vs. local opening displacement at location 4. Little opening until about 70% of peak load illustrates the significant amount of crack closure observed in Hastelloy X.

To this point the results are not surprising and agree with previous measurements that we have made in project D2 on Ti. One difference is in the amount of shielding – in the Hastelloy X case about 70% of peak load , whereas in the Ti case, and most other metals, about 30% of peak load. This is certainly a point of interest and will be further investigated in the future. However, the main goal at this stage of the project was to investigate how an increase in temperature affects these closure results. Figures Cas-4b,c show the effective SIF, measured from the 2x DIC experiments, compared to the theoretical (applied) stress intensity factor for the elevated temperature experiments of 250°C and 450°C. What is immediately evident, even from the 250°C measurement cycle, is that no crack closure is visible above room temperature. As temperature increases further, no change in results is seen, other than the expected thermal softening (which is very small). This is a dramatic shift in a plasticity-based phenomenon from one cycle to the next simply by a very moderate increase in temperature. Note that (a) the 250°C measurement cycle immediately followed the room temperature cycle (which showed a very large amount of closure), and (b) Hastelloy X is a high temperature superalloy which shows little change in properties for such a low temperature increase (only 250°C). This behavior therefore was very unexpected, and will now form the focus of continued efforts to understand why this is the case. The loss of closure as temperature increases would have profound implications for the thermomechanical fatigue life of this material, at least for low values of loading ratio R.



(a) (b) (c)

Figure Cas-4: Comparison of experimentally measured SIF from 2x DIC experiments with theoretical (i.e., applied) value for measurement cycles corresponding to temperatures of (a) 25°C, (b) 250°C, and (c) 450°C.

Approved for public release; distribution unlimited.

3 Management

Executive Director William Dick manages the Center, and along with two UI co-Technical Directors (Glaucio Paulino and John Lambros) work with their research counterparts at AFRL/RBSM. A Science Steering Committee of program participants (UI and AFRL/RBSM) convenes bi-weekly to guide program execution. Collaboration among the partners is frequent and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and visitor office spaces exist at UI to directly support the MSSC. The Directors and Science Steering Committee members are responsible for nurturing the research program, administering the Center, and maintaining and expanding relationships with AFRL/RBSM. This directorate provides the leadership necessary to ensure that the Center identifies the most important research areas, attracts the most qualified researchers, and pursues and completes the work effectively over the long term. A small administrative staff works to execute Center activities.

The MSSC is housed within the University of Illinois Computational Science and Engineering (CSE) Program. CSE is inherently interdisciplinary, drawing faculty, staff and students from 17 departments and requiring expertise in advanced computing technology, as well as in one or more applied disciplines. The purpose of the academic CSE Degree Option is a perfect complement to the goals of the AFRL/RBSM program — to foster interdisciplinary, computationally oriented structural sciences research among all fields of science and engineering, and to prepare students to work effectively in such environments. This academic structure lends itself naturally to the requirements of the MSSC: a free flow of students and ideas across academic departmental, college, and governmental unit lines. A far-reaching Visitors Program has been implemented to encourage close collaboration among the team members. Research offices and computational facilities in CSE space are available for this purpose.

Approved for public release; distribution unlimited.

4 Publications

2010

Carroll J., W. Abuzaid, J. Lambros, and H. Sehitoglu, 2010. "An Experimental Methodology to Relate Local Strain to Microstructural Texture," Rev. Sci. Instrum. 81, 083703.

Domyancic L. and H. Millwater, 2010. "Advances in Bounding Techniques for Aircraft Structures," 2010 AIAA Region IV Student Conference 2-3 April 2010, Houston, Texas, Second place Master's competition.

Efstathiou C., Sehitoglu H. and Lambros J., 2010. "Multiscale Strain Measurements of Plastically Deforming Polycrystalline Titanium: Role of Deformation Heterogeneities," International Journal of Plasticity, Vol. 26, pp. 93–106, 2010.

Gain A. L., 2010. A hybrid technique to extract cohesive fracture properties of elasto-plastic materials using inverse analysis and digital image correlation, MS Thesis, University of Illinois at Urbana Champaign.

Gain A. L., Carroll J., Paulino G. H., Lambros J., 2010. A hybrid experimental/numerical technique to extract cohesive fracture properties for mode-I fracture of quasi-brittle materials, Submitted to International Journal of Fracture.

Kang W.-H., Y.-J. Lee, J. Song, and B. Gencturk, 2010. Further Development of matrix-based system reliability method and applications to structural systems, Structural and Infrastructure Engineering: Maintenance, Management, Life-cycle Design and Performance, Accepted for publication.

Lee Y.-J., and J. Song, 2010. Identification of critical sequences of fatigue-induced failures by branch-and-bound method employing system reliability bounds. Proc. 12th AIAA Nondeterministic Approaches Conference, April 12-15, Orlando, FL.

Lee Y.-J., and J. Song, 2010. Risk analysis of fatigue-induced sequential failures by branch-and-bound method employing system reliability bounds. Journal of Engineering Mechanics, Submitted for review.

Nevill Daniel W., 2010. "Methodology for the Validation of Aircraft Simulations in a Mission Scenario Through the Use of a Validation Tree with Uncertainty," University of Illinois, MS Thesis, April 2010.

Shanmugam V., Penmetsa, R.C., and Tuegel, E., 2010. "Determination of Probability Density Functions of the Cohesive Zone Parameters," 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, AIAA-2010-2515, Orlando, FL, April 12-15.

Smith L., H. Millwater, 2010. "Series System Error-Based Identification of Critical Locations Using Sampling," 12th AIAA Nondeterministic Approaches Conference, April 12-15, 2010, Orlando, FL.

Sparkman D., and H. Millwater, 2010. "FORM-Based Filtering of Limit States," Aircraft Airworthiness & Sustainment Conference, Austin, TX, May 10-13, 2010. First Place Student Competition.

Sparkman D., L. Domyancic, and H. Millwater, 2010. "FORM-Based Filtering of Limit States for Gaussian Random Fields," 12th AIAA Nondeterministic Approaches Conference, April 12-15, 2010, Orlando, FL.

Sucheendran M., Bodony, D. J. and Geubelle, P. H. "Structural acoustic response of a cavity-backed plate in a duct" To be submitted to AIAA Journal.

Approved for public release; distribution unlimited.

2009

Carroll J., 2009. “Quantifying Grain Behavior with Digital Image Correlation,” Society of Experimental Mechanics Annual Conference, Albuquerque, New Mexico, June 2009.

Carroll J., Efstathiou C., Abuzaid W., Lambros J., Sehitoglu H., Hauber B., Spottswood S.M. and Chona R., 2009. “Observations of Grain Level Damage Accumulation in Fatigue,” SEM International Congress and Exposition, Albuquerque, NM, June.

Carroll J., Efstathiou C., Lambros J., Sehitoglu H., Hauber B., Spotswood S. and Chona R., 2009 “Investigation of Fatigue Crack Closure Using Multiscale Image Correlation Experiments,” Engineering Fracture Mechanics, Vo. 76, No. 15, pp: 2384-2398, DOI: 10.1016/ j.engfracmech.2009.08.002.

Carroll J., Efstathiou C., W. Abuzaid, Lambros J., Sehitoglu H., Hauber B., Spottswood S.M., Chona R., 2009. “Observations of Grain Level Damage Accumulation in Fatigue,” Society of Experimental Mechanics Annual Conference, Albuquerque, New Mexico, June 2009.

Domyancic L., D. Sparkman, and H. Millwater, L. Smith and D. Wieland, 2009. “A Fast First-Order Method for Filtering Limit States,” 11th AIAA Nondeterministic Approaches Conference, May 4-7, 2009, Palm Springs, CA, AIAA 2009-2260.

Efstathiou C., Sehitoglu H. and Lambros J., 2009. “Multiscale Strain Measurements of Plastically Deforming Polycrystalline Titanium: Role of Deformation Heterogeneities,” in press International Journal of Plasticity.

Gain A. L., 2009. “A hybrid technique to extract cohesive fracture properties of elasto-plastic materials using inverse analysis and digital image correlation,” MS Thesis, University of Illinois at Urbana Champaign.

Gain A. L., Carroll J., Paulino G. H., and Lambros J., 2009. “Extraction of cohesive Properties of elasto-plastic material using inverse analysis,” 10th US National Congress on Computation Mechanics, Columbus, Ohio.

Kang, W.-H., Y.-J., Lee, J. Song, and B. Gencturk, 2009. “Further development of matrix-based system reliability method and applications to structural systems.” Submitted for publication in Structural and Infrastructure Engineering.

Kim D.-J., J.P. Pereira and C.A. Duarte, 2009. “Analysis of three-dimensional fracture mechanics problems: A two-scale approach using coarse generalized finite element meshes.” International Journal for Numerical Methods in Engineering. Accepted for publication.

O’Hara P., C.A. Duarte, and T. Eason, 2009. “Multi-scale analysis of sharp transient thermal gradients using coarse generalized finite element meshes.” In Tenth US National Congress on Computational Mechanics, Columbus, OH, USA, 16-19 July 2009. Keynote Lecture.

O’Hara P., C.A. Duarte, T. Eason, and D.-J. Kim, 2009. “Generalized finite element analysis of three-dimensional heat transfer problems exhibiting sharp thermal gradients.” Computer Methods in Applied Mechanics and Engineering, 198(21—26.:1857—1871, http://dx.doi.org/10.1016/ j.cma.2008.12.024.

Ostoich C., Bodony, D. J., Geubelle, P. H., 2009. “Coupled computational fluid-thermal investigation of hypersonic flow over a quilted dome surface," Bull. Amer. Phys. Soc., Vol 54(19).

Penmetsa R. C., and Tuegel, E., 2009. “Single Inverse Based Reliability Analysis for Static Strength Failure Modes,” International Journal of Engineering under Uncertainty: Hazards, Assessment, and Mitigation, Accepted for Publication, October 2009.

Approved for public release; distribution unlimited.

Penmetsa R. C., Kable, B., and Tuegel, E. 2009, “Identifying Structurally Significant Items Using Matrix Reanalysis Techniques,” 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Palm Springs, California, May 4-7, 2009.

Penmetsa R. C., Tuegel, E., and Shanmugam, V., 2009. “Rapid Risk Assessment using Probability of Fracture Nomographs,” Journal of Fatigue and Fracture of Engineering Materials and Structures, Vol. 32, 2009, pp.-886-898.

Penmetsa R. C., Shanmugam, V., and Tuegel, E., 2009. “Rapid Risk Assessment using Probability of Fracture Nomographs,” Journal of Fatigue and Fracture of Engineering Materials and Structures, Accepted for publication, June 2009.

Shanmugam V., Penmetsa, R.C., and Tuegel, E., 2009. “Determination of Probability Density Functions of the Cohesive Zone Model Parameters” ASTM Committee E08 of Fatigue and Fracture, Atlanta, GA, Nov 2009.

Sucheendran M., Bodony, D. J., Geubelle, P. H., 2009. “Structural-acoustic interaction of a cavity-backed, clamped, elastic plate with sound in a duct,” Bull. Amer. Phys. Soc., Vol 54(19).

Watts Seth, 2009. Issues in Material Microstructure Morphology. Master’s Thesis. University of Illinois at Urbana-Champaign.

Watts S. E., D. A. Tortorelli, and T. G. Eason, 2009. Arbitrarily High-Ordered Morphological Descriptors for Quantifying the Microstructure of Metal Matrix Composites. 10th US National Conference on Computational Mechanics. Columbus, OH, 16-19 Jul. 2009.

2008

Carroll J., Efstathiou C., Lambros J., Sehitoglu H., Hauber B., Spottswood S.M. and Chona R., 2008. “Multiscale Analysis of Fatigue Crack Growth Using Digital Image Correlation,” SEM International Congress and Exposition, Orlando, FL, June 2008.

Dwyer H., Penmetsa, R.C., and Tuegel, E., 2008. Risk-Based Design Plots for Aircraft Damage Tolerant Design, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Chicago, IL, Apr. 7-10, 2008. AIAA 2008-2077.

Efstathiou C., Carroll J., Sehitoglu H., Lambros J., Hauber B., Spottswood S.M. and Chona R., 2008. “Damage Evolution in Polycrystalline Titanium,” SEM International Congress and Exposition, Orlando, FL, June, 2008.

Efstathiou C., Sehitoglu H., Carroll J., Lambros J. and Maier H.J., 2008. “Full-Field Strain Evolution during Intermartensitic Transformations in Single Crystal NiFeGa,” Acta Materialia, Vol. 56, pp. 3791-3799.

Hauber B., Brockman R., and Paulino G. H., 2008, On Fatigue Crack Propagation in FGMs: Experiments and Simulations, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 333-338.

Lee Y.-J., J. Song, and E.J. Tuegel, 2008. Finite element system reliability analysis of a wing torque box. Proc. 10th AIAA Nondeterministic Approaches Conference, April 7~10, Schaumburg, IL.

Nguyen T., Song J., and Paulino G. H., 2008. Probabilistic Fracture Analysis of Functional Graded Materials - II: Implementation and Numerical Results, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 159-164.

O’Hara P., C.A. Duarte, and T. Eason, 2008. A generalized finite element method for steady-state and transient heat transfer problems exhibiting sharp thermal gradients. In Society of Engineering Science

Approved for public release; distribution unlimited.

2008. 45th Annual Technical Meeting, University of Illinois at Urbana-Champaign, Urbana, IL, USA, Oct 2008.

O'Hara P., C.A. Duarte and T. Eason, 2008. Multi-Scale Finite Element Analysis of Three-Dimensional Heat Transfer Problems Exhibiting Sharp Thermal Gradients. *Computer Methods for Applied Mechanics and Engineering*, Submitted March 2008

Paulino G. H., M.-J. Pindera, R. H. Dodds Jr., F. A. Rochinha, E. Dave and Linfeng Chen, Editors, 2008. Multiscale and Functionally Graded Materials 2006, AIP Conference Proceedings Volume 973; ISBN: 978-0-7354-0492-2.

Smith L., H.R. Millwater, K. Griffin, and D. Wieland, 2008. "Conditional Filtering for Simplification of Aircraft Structural System Reliability Calculation," 10th AIAA Nondeterministic Approaches Conference, April 7-10, Schaumberg, IL.

Smith L., H. Millwater, D. Wieland, K. Griffin, 2008. Advanced Structural System Reliability Methods for Aircraft Structures, presented at the AIAA Structures, Dynamics and Materials Conference, Schaumberg, IL, April 7-10, 2008.

Song J., Nguyen T., and Paulino G. H., 2008, Probabilistic Fracture Analysis of Functional Graded Materials - I: Concept and Formulation, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 153-158.

Song J., W.-H. Kang, Y.-J., Lee, and S.-Y. Ok, 2008. Applications of matrix-based system reliability method to complex structural systems. Proc. IFIP 08-WG7.5, August 6-9, Toluca, Mexico.

Stump F. V., Silva E. C. N., and Paulino G. H., 2008, Topology Optimization with Stress Constraints: Reduction of Stress Concentration in Functionally Graded Structures, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 303-308.

Tuegel E., Penmetsa, R. C., and Shanmugam, V., 2008. "Rapid Determination of the Probability of Fracture for a Cracked Stiffened Panel," 2008 ASIP Conference, San Antonio, Texas, Dec. 2-4, 2008.

Watts, S. E., D. A. Tortorelli, T. G. Eason, 2008. Quantitative description of the morphology of a randomly-distributed particulate composite material. 45th Annual Technical Meeting of the Society for Engineering Science. Urbana-Champaign, IL, 12-15 Oct. 2008.

2007

Duarte C.A., P. O'Hara and T. Eason, 2007. Multiscale adaptive modeling of sharp thermal gradients. In Structural Science Center Peer Review, Urbana, IL, Oct. 2007.

Efstathiou C., Sehitoglu, H., Carroll, J., Lambros, J., Maier, H. J., 2007. Full-Field Strain Evolution during Intermartensitic Transformations in Single Crystal NiFeGa, *Acta Mater.,* Submitted.

O'Hara P., 2007. Finite element analysis of three-dimensional heat transfer for problems involving sharp thermal gradients, M.Sc. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.

O'Hara P., C.A. Duarte and T. Eason, 2007. Adaptive Modeling of Heterogeneous Shells Subjected to Thermomechanical Loads. Poster presentation at Structural Science Center Peer Review, Urbana, IL, Oct. 2007.

O'Hara P., C.A. Duarte and T. Eason, 2007. Analysis of Three-Dimensional Heat Transfer Problems Involving Sharp Thermal Gradients, Ninth US National Congress on Computational Mechanics, San Francisco, CA, Jul. 2007.

Penmetsa R., and Tuegel, E., 2007. Probability Distribution Function of the Product and Ratio of Independent Random Variables using Convolution, *Journal of Multivariate Analysis*, Submitted December 2007

Approved for public release; distribution unlimited.

Song J., and W.-H. Kang, 2007. Matrix-based system reliability method and applications to structural systems. Proc. 18th Engineering Mechanics Division Conference of ASCE, ASCE EMD 2007., June 3-6, Blacksburg, VA.

Song J., and W.-H. Kang, 2007. Risk-quantification of complex systems by matrix-based system reliability method. Special Workshop on Risk Acceptance and Communication, Stanford, CA, March 26-27.

Song J., and W.-H. Kang, 2007. System reliability and sensitivity under statistical dependence by matrix-based system reliability method. Accepted for publication in Structural Safety.

Stump F.V., E.C.N. Silva and G.H. Paulino, 2007. Optimization of material distribution in functionally graded structures with stress constraints, Communications in Numerical Methods in Engineering. Vol.23, No.6, pp. 535-551.

2006

Bellur Ramaswamy R., E. Fried, X. Jiao, and D. A. Tortorelli, 2006. Simulating Solid-Solid Phase Transition in Shape-Memory Alloy Microstructure by Face-Offsetting Method, presented at Multiscale and Functionally Graded Materials Conference, Oct. 15-18, 2006, Hawaii.

Dick William A., 2006. Midwest Structural Sciences Center — A University-Government Partnership, Multiscale and Functionally Graded Materials Conference – FGM 2006, Ko Olina, Hawaii, October 2006.

Duarte C. A., L. G. Reno, A. Simone, and E. van der Giessen, 2006. Hp generalized finite elements for three-dimensional branched cracks and polycrystals, In G. H. Paulino, M.-J. Pindera, R. H. Dodds, and F. A. Rochinha, editors, Multiscale and Functionally Graded Materials Conference – FGM 2006, Ko Olina, Hawaii, 15-18 October 2006. Keynote Lecture.

Hauber B.; Brockman, R. and Paulino, G. H., 2006. On Fatigue Crack Propagation in FGMs: Experiments and Simulations, presented at Multiscale and Functionally Graded Materials Conference M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Nguyen T.; Song, J. and Paulino, G. H., 2006. Probabilistic Fracture Analysis of Functional Graded Materials - II: Implementation and Numerical Results, presented at “Multiscale and Functionally Graded Materials Conference” M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Song J.; Nguyen, T. and Paulino, G. H., 2006. Probabilistic Fracture Analysis of Functional Graded Materials - I: Concept and Formulation, presented at “Multiscale and Functionally Graded Materials Conference” M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Stump F. V., Silva, E. C. N. and Paulino, G.H., 2006. Topology Optimization with Stress Constraints: Reduction of Stress Concentration in Functionally Graded Structures, presented at “Multiscale and Functionally Graded Materials Conference” M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Approved for public release; distribution unlimited.